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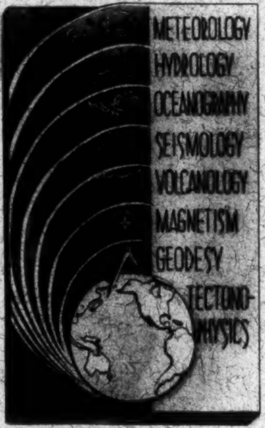
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NOTICE

TWENTY-SEVENTH ANNUAL MEETING, WASHINGTON, D. C.

MAY 27 to 29, 1946.

The Twenty-Seventh Annual Meeting of the American Geophysical Union will be held in the Hall of Government, George Washington University, 21st and G Streets, Northwest, Washington, D. C., May 27 to 29, 1946. Sessions will extend over two or three days, depending upon developments during the planning of the program.

This first announcement of the meeting is an invitation to communicate plans for papers. Titles and abstracts of papers should be sent as soon as possible, and not later than April 15, to the Secretaries of the Union and Sections, as follows:

The Union	Jno. A. Fleming Waldo E. Smith	5241 Broad Branch Road, N.W., Washington 15, D. C.
Geodesy	J. A. Duerksen	U. S. Coast and Geodetic Survey, Washington 25, D. C.
Seismology	L. M. Murphy	U. S. Coast and Geodetic Survey, Washington 25, D. C.
Meteorology	H. D. Harradon	5241 Broad Branch Road, N.W., Washington 15, D. C.
Terrestrial Magnetism and Electricity	D. G. Knapp	3827 W Street, S.E., Washington 20, D. C.
Volcanology	Francis G. Wells	U. S. Geological Survey, Washington 25, D. C.
Hydrology	K. H. Beij	National Bureau of Standards, Washington 25, D. C.
Tectonophysics	M. K. Hubbert	Shell Oil Company, Shell Bldg., Houston 2, Texas.

The Chairman of the Committee on Meetings (J. P. Marble, Smithsonian Institution, Washington 25, D. C.) invites suggestions and comments bearing on the proposed meeting. Offerings relating to papers and symposia bearing on more than one section are especially invited.

Complete manuscripts of papers should be forwarded in triplicate by early May. In preparing papers for presentation, and for publication in the *Transactions*, authors are requested to refer to "Suggestions to Authors" (Trans. Amer. Geophys. Union, pp. 179-182, August 1945); reprints of these suggestions may be secured from the office of AGU.

In transmitting papers and abstracts, advice should be given on time (most papers are allowed from 10 to 20 minutes) and projection equipment required. When papers are written in collaboration, please indicate by whom they will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend the meeting. Papers for publication only are also welcome for consideration for the *Transactions*.

John Putnam Marble, Chairman,
Committee on Meetings

Transactions, American Geophysical Union Volume 27, Number I February 1946

DEVELOPMENT OF CONSTANT-ALTITUDE INSTRUMENTS FOR ASTRONOMICAL OBSERVATIONS

John E. Willis

Abstract--This paper describes the split-telescope astrolabe and the pendulum-astrolabe, which the author invented and assisted in bringing into use for the determination of astronomical longitudes and latitudes from observations of stars whose positions relative to other stars are determined on other instruments, and describes the system of the prospective constant-altitude transit-circle for further use of the principles of these instruments in the fields of geodesy and fundamental astronomy, including the determination of the spherical coordinates of all celestial objects. The most useful form of the constant-altitude transit-circle is expected to be an observatory instrument of about 15 inches aperture for the direct determination of much more accurate spherical coordinates of stars and other objects down to about the 11th or 12th magnitude, along with the latitude, longitude, and azimuth at the observatory. These more accurate star-coordinates are expected to contribute fundamentally to the solutions of many problems of practical and theoretical interest. It is judged that there should be one or more constant-altitude transit-circles in each hemisphere, north and south, and that there should be about 15 photographic zenith-tubes distributed throughout the world in addition to the one at the Naval Observatory in Washington, which has been the best standard of time and frequency and the best base station for the determination of longitudes since 1934. An indefinite number of field-instruments, probably pendulum-astrolabes or photographic zenith-tubes, are needed for determining astronomical longitudes and latitudes to be used in conjunction with geodetic observations for determining the shape of the Earth.

Development of the use of reflex systems away from the zenith--Proceeding from an understanding of the developments of the reflex zenith-tube system by AIRY [see 1 of "References" at end of paper], by ROSS [2], and by WILLIS [3] (about 1923), and from an understanding of the 60°-altitude reflex bent-telescope system [4] of DE LA BAUME PLUVINEL (about 1921), which, like the reflex zenith-tube, used a mercury basin halfway between the nodal point of the object glass and the focus, the writer, in 1940, planned to use additional lenses with the bent-telescope system to make an instrument in which the rays of light from a star would become parallel to each other before striking the mercury. It was realized that such an instrument could be made with an object glass of any size up to about 40 inches, could be made photographic like the photographic zenith-tube, and could, if equipped with a horizontal calibrated azimuth-circle, do about as accurate work over a much larger portion of the sky as the photographic zenith-tube system can do in its small zone, which is of the order of a half degree in width.

With such an instrument, both altitude and azimuth are insensitive to tilts, and any desired refinement in allowing for the effects of tilts is obtainable by the use of moderately sensitive spirit-levels.

At that time, the writer had in mind, especially, the more accurate determination of the constant of precession by measurement of the motions of stars over a long period of time, and the more accurate determination of time by the use of a greater number of stars than can be observed with a photographic zenith-tube. For both of these observing projects the use of a small zenith distance, of the order of five or ten degrees, would be desirable in order to diminish greatly the importance of errors of calibration of the azimuth-circle. The completely fundamental character of the system (or, perhaps, the importance of directly working with twelfth magnitude stars) was not fully appreciated until after a small instrument of this kind, but without an accurate azimuth-circle for field-determination of longitude and latitude by the method of timing of stars at a constant altitude, was completed and the subject was reconsidered.

A little later, in reading the reports of S. C. CHANDLER regarding the almucantar (a telescope with a horizontal transit-reticle, the whole instrument being floated on mercury while directed at a constant altitude) to see if he had considered the simultaneous use of two almucantars at different altitudes, the writer found that CHANDLER, about 1886, called attention to the fact that an observing method which would give relative azimuths and relative times of transits of stars over a circle of constant altitude would be a fundamental method, that is, would determine spherical coordinates of celestial objects and of the pole and the zenith. CHANDLER also wrote that, although he did not see the way to that end, he believed an instrument would be found eventually which would be well adapted to such observing. The reflex constant-altitude transit-circle system, discussed in detail later, or the closely similar system of the pendulum-astrolabe with accurate azimuth-circle calibration and photographic recording, is such a system as CHANDLER hoped and believed would be found. The self-correcting properties of the reflex optical system of the photographic zenith-tube, bent-telescope astrolabe, pendulum-astrolabe, and constant-altitude transit-circle, are shown in Figure 1. O is a position of the nodal point of the object glass, M is the horizontal mirror, R is a position of the reticle. The primes refer to two conditions of tilt, the tilt being performed so that the distance from the mirror to a point (C) midway, mechanically, between the object glass and the reticle, remains constant. It is seen that the image of the star is formed at the reticle even if the instrument is tilted a noticeable amount. With the photographic zenith-tube, R represents the center of the plate, and the points O and R are made coincident, mechanically, with C.

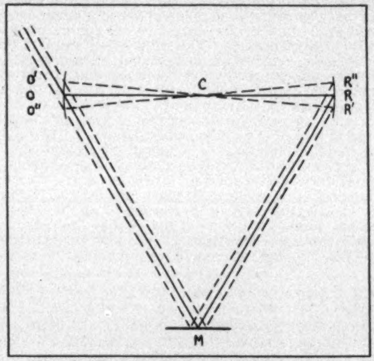

Fig. 1--Sketch indicating self-correcting properties of reflex optical system

It was also realized, about 1940, or perhaps much earlier, that a constant-altitude transit-instrument without an accurate azimuth-circle would make possible the determination of fundamental coordinates except at high latitudes (and therefore also on the equator) if used in conjunction with a diagonal-vertical transit-instrument observing transit-times of stars over two vertical circles at a single measured angle to each other. With this system, the earth itself would interpolate the declinations as well as the right ascensions, and mean refraction would be eliminated. This system should be kept in mind in planning astronomical work near the equator.

The WILLIS split-telescope astrolabe--When the need arose for additional instruments for use by field parties of the United States Army in determining longitude and latitude for aerial mapping, the writer called the attention of J. R. BAKEWELL, Chief Warrant Officer with the Engineer Board, Corps of Engineers, United States Army, Fort Belvoir, Virginia, to the non-prismatic bent-telescope system with the modification including additional lenses to assure insensitivity to the height of the mercury. It was realized that the optical system in front of the mercury basin constituted a Galilean telescope of power two, and that the rest of the system could be modified to have any equivalent focal length which might be desired to diminish the size of the reticle-lines relative to the size of a star-image. Consequently, it was thought at first that the telescope of an engineers' transit would be used after the reflection from the mercury basin and that the instrument would take the form of an attachment to an engineers' transit. This possibility had been in mind since December, 1940. But engineers' transits were scarce also, and it was concluded that it would be better to plan an independent instrument, which, for use with the contemplated timing at a constant altitude without accurate azimuth-measurement, did not need an accurate circle.

A successful instrument of this kind [5] was made in 1942-43 at the United States Naval Observatory Material Department for the Army Engineer Board. A further novel feature, curved reticle-lines on glass to correspond to small circles of constant altitude, was introduced. A rigid mirror, which could be introduced into the rays from the object glass, reflected light to a low power eye-piece for finder purposes.

This instrument is referred to as the WILLIS split-telescope astrolabe. Its optical system is one of those which can be used for the prospective constant-altitude transit-circle for determining fundamental spherical coordinates of stars and observing stations.

The WILLIS pendulum-astrolabe--While the improved split-telescope astrolabe was being built, the writer tried out air damping of a pendulous rigid mirror as a prospective replacement for the sloped-basin damping of the mercury mirror, and found it to be effective in bringing the mirror to rest within a few seconds. An experimental observing instrument using this device and omitting the central lenses of the split-telescope astrolabe, was then made at the Naval Observatory Material Department for the Army Engineer Board, represented by W. S. LITTLE, Captain, of the Mapping Branch. For both instruments mentioned, the lenses were made in the Optical Instruments Section of the United States Bureau of Standards under the direction of I. C. GARDNER, and the reticles with curved lines were made by R. DAVIS of the Photographic Section of the Bureau of Standards.

A pilot production model of the pendulum-astrolabe [5] was developed in 1943, for the Engineer Board, at the DAVID WHITE Company, Milwaukee, principally by CHARLES ROTHWEILER, President of the Company, and SVEN PETERSEN, with the cooperation of W. S. LITTLE and the writer, who at that time was Astronomer at the United States Naval Observatory.

The optical system of the visual pendulum-astrolabe, or a visual constant-altitude transit-circle, drawn for an altitude of 60° is shown in Figure 2. If the instrument is equipped with the photographic recording system of the photographic zenith-tube, the photographic plate replaces the reticle, and no eyepiece is used on the instrument; the photographic plate is then measured by moving it measured amounts under a compound eyepiece or microscope, in an assembly called a measuring engine or two-coordinate measuring instrument.

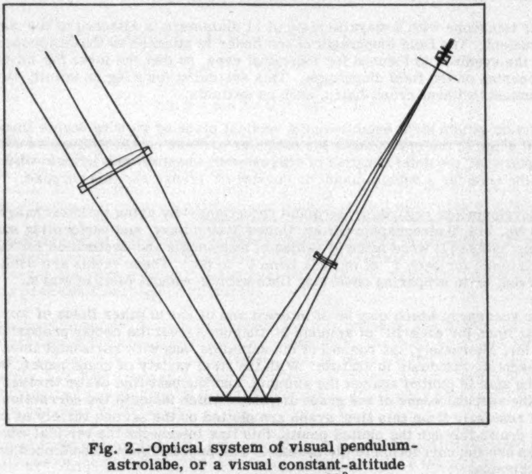

Fig. 2--Optical system of visual pendulum-astrolabe, or a visual constant-altitude transit-circle, altitude 60°

About 70 pendulum-astrolabes were built in 1944-45. The production instruments [6] are made for visually observing the times at which stars cross circles of constant altitude near 60°. The tripods on which the instruments are mounted are 44 inches high.

The light of a star passes through an object glass of 53 mm aperture, reflects from a pendulous horizontal mirror, passes through an achromatic BARLOW lens to double the effective focal length to a value of 800 mm, focuses at a glass-reticle with five curved lines of constant altitude, and passes through an orthoscopic eyepiece of 10 mm equivalent focal length to the eye. The angular magnification of the instrument is eighty.

The frame supporting the mirror is suspended by two sets of springs, similar to those used with clock-pendulums, though spaced more widely, permitting both fore-and-aft and transverse motion. To compensate the effects of the elasticity of the springs in causing the mirror to deviate from the horizontal position when the whole instrument is tilted, the object-glass is located several millimeters closer to the mirror than it would be if the mirror remained exactly horizontal; the proper position of the object-glass is established by observing upon a fixed collimator and adjusting until the setting does not change appreciably when the instrument is tilted fore-and-aft over the range of freedom of the pendulum, about ten minutes of angle.

The air-damping system consists of crossed planes suspended below the mirror and surrounded by stationary plane surfaces with a clearance of one-half mm all around. The pendulum comes to rest about six seconds after it has been disturbed.

Spirit levels with two-mm divisions per minute of tilt are provided for setting up the instrument and leveling with a four-screw system. If desired, readings of the spirit-levels may be recorded; the effective altitudes of the instrument will then be controlled within about a hundredth of a second of arc. Without reading the levels, the stability of altitude is about a tenth of a second of arc or angle, if the leveling of the instrument is accurate to one minute of arc or angle.

The instrument is provided with an azimuth-circle that can be shifted, and with endless-tangent-screw motion in azimuth relative to the azimuth-circle. The tangent-screw rotates once per degree of azimuth and has a drum divided to five minutes and numbered at each ten minutes of azimuth. The tangent-screw is held disengaged for quick motion, if the azimuth-circle is clamped.

A finder telescope with a magnification of 11 diameters is attached to the observer's left side of the instrument. The field diaphragm of the finder is attached to the telescope tube and does not move when the eyepiece is focused for individual eyes, so that the focus for infinity can be obtained by focusing on the field diaphragm. This system of focusing on infinity is desirable for other instruments without cross-hairs, such as sextants.

A reflection-prism sight establishing a vertical plane by viewing double images is attached to the finder of some of the instruments for obtaining azimuth-circle settings on definitely identifiable naked-eye stars for the determination of approximate longitude and latitude when needed. This eliminates the need for a bubble-octant or surveyors' transit for this purpose.

Some developments regarding astrolabe reductions--By using an interchange of arguments in Publication No. 214, Hydrographic Office, United States Navy, and performing some additional computations, tables [7] were made of values of hour-angle and declination for 60°-altitude for each 5° of azimuth for each 1° of latitude from 0° to 80°. These tables are useful in identifying stars observed, or in preparing observing lists with or without plots of stars.

Another accessory which may be of interest and of use in other fields of work is graph paper with vertical lines for each 10° of azimuth at distances from the center proportional to the values of the sine (or, alternately, the cosine) of the azimuths, and with horizontal lines making a uniform scale representing residuals in altitude. With the first variety of graph paper, the residual in altitude for each star is plotted against the azimuth, and the best line drawn through the plotted points intersects the vertical edges of the graph at values which indicate the corrections to longitude and altitude. If residuals from this first graph are plotted on the second variety of graph paper and the best line is drawn through the plotted points, this line intersects the vertical edges of the graph at values which are the correction to the latitude. The process may be continued on the first kind of paper, if desirable.

For deriving longitude and latitude from the times of transit of stars over a reticle line of the astrolabe without making any preliminary assumptions about the longitude and latitude except for identifying the stars, several procedures were worked out, the most fundamental procedure being the following:

The times of observation are converted to Greenwich sidereal times, using the evidence from the radio time signals, and the Greenwich hour angles are computed by subtracting the right ascensions of the corresponding stars. Then, for each observation on the same reticle-line, there is an observation equation,

$$(\cos \delta \sin \mathrm{GHA})A + (\cos \delta \cos \mathrm{GHA})B + (\sin \delta)C = 1$$

in which

δ is the declination of the star,

GHA is the Greenwich hour-angle of the star,

and

$$A = \cos L \sin \lambda / \sin h$$

$$B = \cos L \cos \lambda / \sin h$$

$$C = \sin L / \sin h$$

in which

L is the latitude,

λ is the longitude, and

h is the altitude.

The observation equations are solved for A, B, and C as numbers, and then the latitude, longitude, and altitude are derived from the equations for A, B, and C, using the equivalent equations,

$$\tan \lambda = A / B$$

$$D = \cos L / \sin h = A / \sin \lambda = B / \cos \lambda$$

$$\tan L = C / D$$

$$\sin h = \sin L / C = \cos L / D.$$

The photographic reflex constant-altitude transit-circle system for determining fundamental spherical coordinates of stars and points on the Earth--The full exploitation of the practical possibilities of the self-leveling reflex-systems for observing stars will include the direct fundamental determination of spherical coordinates of the highest accuracy of stars down to about the 11th or 12th magnitude by effectively measuring azimuth and time of transit at circles of constant altitude.

This method, besides being alternate to methods previously used in attempting to get star-coordinates of greatest accuracy, which is an important consideration in such work, promises to be much more accurate and very economical and convenient in use, avoiding troublesome effects heretofore met and processes heretofore required.

It is estimated, preliminarily, that an instrument for this purpose, combining features already in highly satisfactory use in the photographic reflex zenith-tube, the split-telescope astrolabe, the pendulum-astrolabe, and other scientific instruments, can be built and put into routine use at a cost of approximately $25,000, using an aperture of about 15 inches, a focal length of about 15 feet, photographic observing in a two-degree or a one-degree field, and a very accurately calibrated azimuth-circle with one-degree divisions.

The latitude used first will probably be between 20° and 45°, and the altitude used first will probably be the altitude of the celestial pole, the same, numerically, as the latitude. Perhaps the same instrument will operate conveniently at either of two chosen altitudes, and thus cover additional areas of the sky to increase everyday usefulness. Two instruments, one in each hemisphere, north and south, would cover all areas of the sky, even if each instrument operated at a single altitude. One instrument, used in each hemisphere in turn, would cover all areas of the sky, though, of course, not continuously.

The reflex optical system will assure control of the altitude of the instrument with an accuracy of a hundredth of a second of arc, or with even greater accuracy.

The two-coordinate photographic recording and measuring system of the WILLIS photographic reflex zenith-tube system, already in continuous use at the United States Naval Observatory since 1934, will be used with additional provision for setting the direction of motion of the plate carriage at any position angle. Normally, four exposures will be made on each field (which may contain a number of stars whose positions are desired), with the position angle of the plate and carriage and track changed 180° between exposures.

Electric contacts will record the clock-times when the plate passes certain mechanical positions.

The coordinates of the star, relative to the center of rotation of the track, and corresponding to the mean of the times recorded electrically, will be computed from measures of the images on the plate with a two-coordinate measuring engine, as with the photographic zenith-tube work. These plate-coordinates will be used with readings of the azimuth-circle to get quantities which, when used with similar quantities from observations of some or many other stars, will give new or improved values of the right ascension and declination of the star and an improved value of the latitude.

For convenience, and perhaps with further economy, the photographic reflex constant-altitude transit-circle may utilize, as an auxiliary instrument, a WILLIS photographic reflex zenith-tube at about the same latitude (nearby, or within a few hundred miles, if the unpredictable motion of the Earth's axis is to be accounted for without awaiting an international comparison of results), with radio time-connections directly or indirectly if not at the same site. Then some of the zenith-tube stars may be observed with the zenith-tube to get local sidereal time and the temporary latitude, and other zenith-tube-stars may be observed with the constant-altitude transit-circle to get the effective altitude and the effective azimuth-circle correction of the constant-altitude transit-circle. With these observations as a basis of reduction, any individual stars or groups of stars whose positions are desired for some particular purposes, such as for the determination of the position of a faint comet, planet, or nebula, which may have been photographed shortly before with one of the great reflecting telescopes, may be observed with the constant-altitude transit-circle, and their positions may be calculated without any known cause for delay.

With methods heretofore used for fundamental determinations of spherical coordinates, great difficulties would be encountered in attempting to use the large apertures and long focal lengths needed to deal directly with the faint stars whose accurate positions are desired for further progress in position astronomy. The difficulties encountered with the smaller sizes of fundamental instruments already used have never been overcome. This statement does not apply to the photographic reflex zenith-tube, which is not a fundamental instrument until it is modified to become a constant-altitude transit-circle. With the constant-altitude transit-circle system, whether the reflex principle is used or is not used, apertures up to about 40 inches are practicable; but only with the use of the reflex principle will the results be as free from the effects of tilt as is desirable because it is possible, as proved by the performance of the reflex instruments already existing.

The horizontal position of the plane of the divided circle of the constant-altitude transit-circle system is the ideal position for obtaining accurate results with a divided circle, because the action of gravity is unchanging.

The constant-altitude transit-circle system does not require a knowledge of the complete vertical refraction, which is fundamentally necessary for work with the meridian transit-circle, but requires only a knowledge of changes which may occur in the effective altitude. These can be measured by observing zenith-tube stars, or by observing stars both east and west of the meridian. Probably the instrumental altitude itself will be found to be constant to a high degree of accuracy; whether constant or not, it will be controlled without any man-made uncertainty. Changes in the effective altitude because of changes in astronomical refraction due to air temperature and air pressure changes will be computed accurately from tables developed by the writer and published in 1941 [8], tables which are accurate enough for meridian transit-circle work even if such work should eventually be made much more accurate than it is at present.

Where continuing uniform radio time-signals are well received, it is not necessary to have a local clock to carry on work with the zenith-tube and constant-altitude transit-circle. Equipment for recording such signals (for example, those of WWV, the National Bureau of Standards station) is already available, such as that developed by E. A. HALBACH at Marquette University.

The supremely accurate results of the WILLIS photographic reflex zenith-tube system, and the reliable action of the reflex astrolabes observable with laboratory precision, assure the success of the photographic reflex constant-altitude transit-circle system.

With it in operation, accurate fundamental star-places will be available on short notice for stars of all magnitudes down to those faint enough and plentiful enough to be used directly as comparison stars in the small fields of the great telescopes. The great uncompleted efforts of the past for the formation of the Astrographic Catalog and the A. G. catalogs for the sake of the fainter stars will be avoided. The number of classes of fundamental accuracy of star coordinates will be reduced from four or five, with accuracy in use ranging from nearly 0.2 to 1 second of arc, to one or two, with accuracy in use of 0.01 to 0.10 second of arc.

It will then be practicable to relate to each other accurately the coordinates of the Earth's axis and the coordinates of all astronomical objects, including the extra-galactic nebula. A great many special problems, such as the determination of the masses and distances of the sun, moon, planets, and stars, will be more easily and accurately treated.

It will become worth while to use an accurate instrument like the photographic zenith-tube for field determinations of longitude and latitude because accurate places of all stars which may be used will be available. Data regarding the motions of the Earth's axis within the Earth will accumulate; the complete motion will be observable from a single observatory if the Earth is rigid. If the Earth is not fixed in shape, the changes will be measured.

It is hoped that a first constant-altitude transit-circle will be put into operation, perhaps near Milwaukee, by 1948, as an appropriate celebration of the centennial of AIRY'S invention of the first reflex zenith-tube system, and to include it as part of the progress in science and world affairs contributed by the people of Wisconsin during the first hundred years of the statehood, the Centennial of which will be celebrated in August and September of the same year.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

TRYGVE STRAND: Structural petrology of the Bygdin conglomerate, Norsk Geol. Tidsskrift, v. 24, pp. 14-31, 1945.

The Bygdin conglomerate is a highly deformed conglomerate below the Scandinavian Highland overthrust. The pebbles are drawn out in a NW-SE direction and are also folded with axes paralleling the maximum axis of the pebbles and pitching 10°-20° NW. Bygdin is located in the highlands approximately at Latitude 61°40′ North and Longitude 9° East. The problem is similar to that discussed by Anders Kvale and F. C. Phillips [see Reviews and Abstracts, this issue, pp. 14 and 34].

The conglomerate occurs in an asymmetrical anticline pitching NW. Stretching parallels the fold-axis. Small-scale folding occurs as wrinkles and folding of pebbles into canoe-shaped three-dimensional bodies with the same axial pitch. Cross joints are conspicuous normal to stretching. The average ratio of pebble-dimensions is approximately 6:2:1. Eighteen quartz and four sericite diagrams show the results of a fabric-analysis. One diagram shows poles of bedding and cleavage, and stretching directions, and another one shows poles of joint-planes. All diagrams have been rotated into the horizontal plane and the author suggests the same treatment in all regional studies for easy comparison.

The salient feature in all diagrams from the conglomerate, except D1, is a girdle with the direction of stretching as axis. Quartz maxima occur 30° or less from the horizontal plane on either side. Symmetry is never perfect and in many cases asymmetry is distinct. Fabric-orientation is constant in space and independent of S-planes.

If the direction of movement were interpreted on the basis of fabric alone, a NE-SW direction would have to be assumed [see also A. Kvale, 1945]. Field-evidence, however, shows a southeastward movement in the Caledonian overthrust region and "accordingly we have folding axes in the direction of tectonical transport, and this is by no means particular of the present area." It has been observed and described often in the literature [Foslie, 1941; Th. Vogt, 1927]. Two interpretations are suggested: two separate acts of deformation or one act of movement and deformation. The writer favors the second alternative because (1) separate foldings in the same area follow the same trend lines, and (2) the two directions are intimately connected and can supersede each other.

The writer interprets the folding with northwest axes as due to triaxial deformation. He refers to earlier discussions by Martin (1935) and agrees with that author. He then refers to the Moine schist investigation by F. C. Phillips (1937) whose area is very similar to the Norwegian problem. Strand feels that "a comparison with the Bygdin area will at once annihilate this argument". . . . (of two deformations normal to each other). In the Bygdin area the possibility of pre-Caledonian deformation is excluded.

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SVEN FØYN: Spalteganger i Sør-varanger (English summary), Nórsk Geol. Tidsskrift, v. 25, pp. 127-145, 1945.

The coastal area of northern Scandinavia in the vicinity of Kirkenes, Petsamo, and Murmansk is transected by innumerable dark dikes. Their compositions are diabase, spessartite, oceanitic dikes, and quartz diorite. The map shows only dikes that are wider than ten meters; some reach 80 meters.

Two major trends are obvious: N 25° W and N 25° E. A third direction about E-W is represented also but is much less common. The dip is vertical or very steep. More than 50 dikes strike NW, about 30 strike NE, and about ten are shown in the E-W direction.

The trend of the (pre-Cambrian) gneisses is mostly N 40° W. It is suggested that the dike-pattern may represent two shear planes. The age of the dikes is uncertain, they may be late pre-Cambrian or late Caledonian or younger. Several ages may be represented.

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NUMBER OF CONDITION-EQUATIONS IN A TRIANGULATION-NET

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The usual procedure for determining the number of condition-equations in the adjustment of a triangulation-net is to build up the figure point by point. This method will give the number of angle and side equations, then azimuth, length, latitude, and longitude equations are added to obtain the total number [see 1 of "References" at end of paper].

In a complicated net, it is advisable to have a check on the total number of equations involved. The total number is given by the formula

$$N = V - 3S_n + S_u$$

in which N is the total number of equations, V is the total number of observed directions excluding those on lines fixed by previous adjustment, S_n is the total number of new stations, and S_u is the total number of unoccupied new stations. This formula is based on the fact that two lines determine a new point and each additional line to this point from established points adds two equations if the line is observed in both directions or one equation if the line is observed in one direction.

In Figures 1, 2, and 3, the heavy lines have been fixed by previous adjustments. The heavy circle in Figure 2 is a fixed station. Directions which are not observed are shown by broken lines.

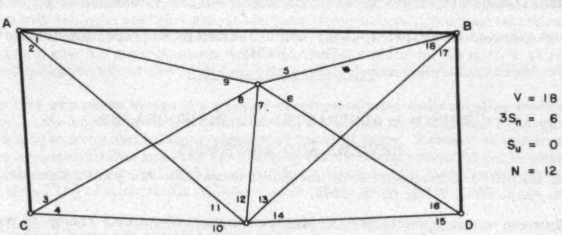

Fig. 1--Triangulation-net with two new stations

In Figure 1, it can be seen that the total number of equations is 12. If line AB is omitted, leaving the fixed lines AC and BD, then the Figure requires azimuth, length, latitude, and longitude equations, but the total number of equations is unchanged. Therefore, the above formula must include all equations in the net.

In case of a fixed station, that is, position-tie only, this should be considered a new station, then two equations are added, one for latitude and one for longitude (see Fig. 2).

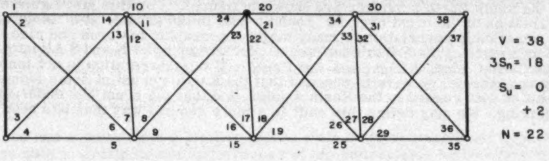

Fig. 2--Triangulation-net with six new stations

When a fixed station is connected to any other fixed station, with directions observed to new stations only, then the fixed station should be considered a new station and two equations added to the number obtained by the above formula (see Fig. 3).

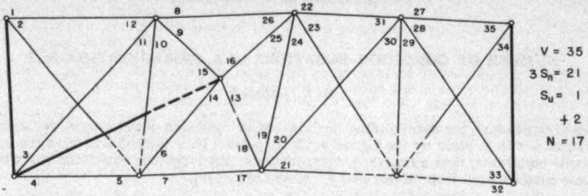

Fig. 3--Triangulation-net with seven new stations, one not occupied

With any LAPLACE azimuths or base-lines in the net, one equation is added for each condition introduced thereby. This is also done for methods previously published [1].

The examples given above include the problems which are likely to occur in the observations of a triangulation-net.

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Washington, D. C.

(Manuscript received December 7, 1945; communicated paper; open for discussion until July 1, 1946.)

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

F. A. VENING MEINESZ: Spanningen in de aardkorst tengevolge van poolverschuivingen, Vers. Ned. Akad. Wet., v. 52, no. 5, 1943.

In this paper the writer investigates the stresses brought about by a change in position of the rigid Earth's crust with regard to the axis of rotation of the Earth; the crust has been assumed to have the same thickness everywhere and to behave as an elastic body. Neglecting the bending stresses in the crust, the equations give the conditions of equilibrium and the relations between stresses and strain. If the vertical component s_{ρ} of the crustal displacement is supposed to be known over the whole surface, we may derive the stresses and the other components of the displacements from these equations. For a rotation of the crust round an axis in the equator over an angle θ we thus obtain the formulas (8), where δ and α are polar coordinates with regard to this axis and where θ and α are counted clockwise from the north direction.

Basing himself on the theories of Huber-Hencky and Bylaard (formulas 12 and 13) for the originating of plastic deformation in elastic media, the writer has determined the resulting curves of shear over the Earth's surface. This net for a hemisphere round the axis of the crustal rotation and for the whole Earth's surface are shown in figures. For this last figure he has assumed a clockwise rotation of the crust over 70° round a pole in the equator at 0° longitude. This last net shows a remarkable correlation to many major topographic features and also the shearing patterns of large parts of the Earth's surface as, for example, the N and S Atlantic, the Indian Ocean and the Gulf of Aden, Africa, and the Pacific. If this correlation is not fortuitous, and this does not appear probable, we have to suppose that the Earth's crust at some moment of its history has indeed shifted with regard to the Earth's poles, and that the crust has undergone a corresponding block-shearing. We may define this shift in a more general way than has been done above.

AUTHOR

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ON LONG-PERIOD SEISMOGRAPHIC DISTURBANCES

Florence Robertson

Abstract--A series of experiments was carried out at Saint Louis using the MACELWANE-SPRENGNETHER horizontal component electromagnetic seismometers working in synchronism with type H-S, L and N galvanometers having a period of twenty seconds; both the seismometer and the galvanometer were critically damped. With this equipment some more or less regular long period disturbances were recorded. These disturbances were finally eliminated by operating the seismographs in a seismic vault in which both the temperature and the humidity were controlled. While no physical explanation for this can be given at the present time, it appears worth while to point out that these results are similar to those found by MILNE in Tokyo, the United States Coast and Geodetic Survey in Honolulu, and by SHAW in England.

In 1939 a series of experiments [see 1 of "References" at end of paper] was instituted at St. Louis for the purpose of making a detailed study of phase relationships of certain teleseismic waves. The first of these was a modification of the tripartite station used by RAMIREZ [2] in his study of microseisms. On the instrumental side, a MACELWANE-SPRENGNETHER horizontal seismometer working in synchronism with a twenty second Type HS LEEDS and NORTHRUP galvanometer, both the seismometer and the galvanometer being critically damped, was found to minimize satisfactorily the microseisms and at the same time magnify, electromagnetically, the earthquake waves to be studied without reaching the instability point of the seismometer. In fact, two of these instruments, one for a north-south component and the other for an east-west component, have been in continuous operation at the Saint Louis University Gymnasium seismograph vault ever since.

A further test was made to see if a greater electromagnetic magnification were desirable. This consisted in the replacing of the seismometer coils used by RAMIREZ by larger coils; that is, coils having a larger area and a larger number of turns of wire. Actually it was found that so much magnification was undesirable because the lines on the seismogram could not be separated even for those earthquakes which were not strong enough to be recorded by instruments other than nearby BENIOFFS. Hence the original coils of the seismometers were reinstated.

The next step in this investigation was the establishment of the other two members of the tripartite station. For that member to the west of the Saint Louis University Gymnasium, a closet space under the stairs, on the ground floor of the Science Building of Fontbonne College, was selected. The seismograph, recording drum, galvanometer stand, etc. were placed on the concrete floor. As soon as the station was put into operation it was found that during the daytime some more or less regular long period vibrations were recorded. The character of these disturbances was somewhat similar to those seen on the records published by the Fordham station [3, 4], reported from WESTON [5], and observed on some of the records borrowed from the other stations, particularly those having long period BENIOFFS.

The equipment at Fontbonne was then moved [6] to the basement of the HEINRICH home where a special pier was built for it and the whole was enclosed in a separate room. However, the records were still "disturbed" during the daytime.

The Maryville Station used by RAMIREZ was to be the third member of the tripartite station; that is, the auxiliary station south of the Saint Louis University Gymnasium. Only a small portion of the record, after modification of the equipment, was seismically quiet; this was during the daytime when the Fontbonne records were the most disturbed.

RAMIREZ had had something of a similar nature when he first started his tripartite station. However, he was able to eliminate the disturbances of his instruments by covering the seismometers with many layers of boxes and tarpaulin. He seemed to be of the opinion that the disturbances of his instruments were due to air currents within the room in which the instruments were placed.

Hence, at the time of the installation precautions were taken to isolate the longer period instruments from their surroundings so as to prevent air currents from disturbing them.

Since the seismically quiet part of the Maryville records corresponded to the most disturbed portion of the westerly members of the tripartite group, and since no other location for the southerly station was available, the project was abandoned.

Shortly after the abandonment of the tripartite station, the disturbances noted at Fontbonne and Maryville Colleges and at the **HEINRICH** residence appeared on the seismograms from the Saint Louis University Gymnasium vault. Furthermore, the appearance of these disturbances could be correlated with the improper operation of the **CURTISS** dehumidifier. This dryer was installed in 1937.

The **CURTISS** Manufacturing Company had, upon request, inverted the mechanism of the dryer so that the intake is at the top and the fan or blower as near the floor level as possible. This was done so that air currents would not be set up which would strike at the instruments directly. Since the Gymnasium vault consists of only one small room, this arrangement did result in the fan's blowing the dried air directly against the bottom of the pier. **RAMIREZ** had found it necessary to fasten a curtain across the front of the dryer so as to lessen the force of the air from the fan. At least, the use of the curtain in front of the dryer did eliminate the disturbance of the "microseism seismographs."

With the longer period instruments, it was found that a heavier curtain was required and also that this curtain must be fastened much more tightly.

Such blocking off of the dryer resulted in its frosting over and hence becoming ineffective. Just as soon as this happened, the disturbances reappeared on the seismograms. Experience showed that there were short time-intervals--just after the fan was blocked off before the dryer froze over and just after it became operative again, after defrosting--during which time the disturbances ceased.

In order to prevent the air-currents from the fan from striking the pier directly and at the same time to leave the dryer sufficiently open to prevent its frosting, a heavy curtain was hung from the ceiling separating the vault into two compartments with the dryer in the one compartment and the pier and seismographic equipment in the other. A chain was run through a hem at the bottom of the curtain to insure contact between the curtain and the floor of the vault. This, however, did not eliminate the disturbances. In each instance, the galvanometer operating on an open circuit gave a straight line on the seismograms.

N. P. REEFF, who had charge of the routine care of the instruments, observed that whenever the vault became too cold the dryer still frosted over and then the oscillations began. On the other hand, when the dryer had been turned off completely, after a few hours of quiesence, the oscillations began again. Even though no reason for such a causal-effect relationship was apparent, a small electric heater was hung on the wall of the vault near the ceiling with its reflector directed at the coils of the dryer from a distance of about six or eight feet. With the heater on to prevent the dryer from frosting and the dryer operating to keep the relative humidity at about 50 per cent, the disturbances have been eliminated. The heater is now operating on a thermostat and the dryer on its humidistat. When either the one or the other or both is inoperative for any length of time, the oscillations reappear. Furthermore, these disturbances begin to die down immediately after restoring the heater-dryer arrangement to proper operating conditions and completely disappear within a few hours. In fact the suddenness of the response is one of the most puzzling features of the observed phenomena.

One of the **MACELWANE-SPRENGNETHER** horizontal seismometers working in synchronism with a twenty second Type HS **LEEDS** and **NORTHRUP** galvanometer was set up as an east-west component seismograph in the Florissant seismograph vault. Here the unwanted oscillations appeared on the seismograms immediately even through the dehumidifier is in the developing room and not in the instrument room, and an outside ventilator is provided in the developing room. In former years, something of the same general character was observed occasionally on the north-south **GALITZIN-WILIP** seismograms. Here too the installation of an electric heater, with its reflector directed at the coils of the dryer, eliminated the disturbances.

In this connection we must remind ourselves that these experiences and ideas are not as new as we had at first thought. I quote [7]:

> With Mr. SHAW'S help the MILNE-BURGESS machine was dismounted from its pier at Shide, and remounted in the dugout some few miles away. At some considerable personal trouble and inconvenience Mr. BURGESS kept the machine running for a few weeks. (It was necessary to keep a pump going to avoid having the dugout flooded.) No very satisfactory results were obtained, the wandering of the trace being just as serious as at Shide, and the experiments came to a natural end when the dugout was reclaimed for military purposes. The main conclusion which emerged from the experiments was that rain had more to do with the wandering of the trace than had temperature. After rain the lines became much congested; when the rain ceased they were unusually expanded, returning to normal separations when the weather had been fine for a few days. . . . .

A check through the Shide circulars discloses many references to "air-tremors," "morning-tremors," "disturbances," etc. A study of the periods reported for some of these corresponds to the longer period disturbances found in the above mentioned series of experiments. Quoting again [8]:

> According to Professor MILNE this effect is associated with a falling temperature.

A further quotation [9]:

> As some evidence of a connection between air-tremors and fall of temperature had been adduced, in the month of November a lamp was introduced into the seismograph room to check the fall of temperature during the night, and thus prevent these disturbances, but without effect. However, in January, 1900, more heating power was used, and now the tremors have almost entirely disappeared.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

ANDERS KVALE: Petrofabric analysis of a quartzite from the Bergsdalen quadrangle, western Norway, Norsk Geol. Tidsskrift, v. 25, pp. 193-215, 1945.

The Bergsdalen quadrangle is about 30 km east of Bergen in an area of intensely deformed quartzites, mica schist, altered rhyolite, dacite, basalt, and granodiorite. Stretching is extreme in an east-west direction or slightly north or south of east. Pebbles in conglomerate have assumed the shape of walking sticks (1 by 3 by 100 cm). Lineation pitches 9° west and cross joints are normal to it.

Fabric analysis (biotite, muscovite, and quartz) shows tendency toward girdles normal to lineation and high concentration of mica-poles in a maximum corresponding to a plane S_3. Quartz maxima of 37.5 per cent are 52° from the mica maximum. All the quartz-grains show preferred orientation.

The fabric is homogeneous and the symmetry monoclinic. The maximum pebble-axis is the lineation, intersection of S-planes and axis of a B-tectonite. "This conclusion is, however, in strong contrast with the evidence gathered by structural investigations in the field. For details must be referred to a monograph on the quadrangle, which will be published in Bergens Museum Årbok. Here shall be mentioned only that the field observations show, in my opinion with absolute certainty, that the whole complex to which the quartzite belongs has been thrust eastward parallel to the lineation, and that the lineation was formed during the thrusting. The immense stretching of the rocks, with elongation of conglomerate pebbles as much as five to ten times their original length, is in itself a proof of considerable tectonic transport parallel to the lineation. We are thus forced to reject the results of the preliminary determination of a and b axes."

The paper is significant in view of the general tendency to assume movement-directions as necessarily normal to b or B in fabric-analysis. Very similar pebble-elongation has been described from other parts in the Scandinavian Highlands [Goldschmidt, 1916]. Rodding in Scotland has also been investigated recently and the general situation is comparable [Phillips, 1945, see Reviews and Abstracts, this issue, p. 34].

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JAMES CAMERON: Structural features of the grey granites of Aberdeenshire, Geol. Mag., v. 82, pp. 189-204, 1945.

The object of this investigation is an analysis of the orientation of joints, minerals, and "bubble trains" in quartz, and a study of the "ways" of the granite, and a correlation of these phenomena.

Two quarries were studied and 27 orientation diagrams prepared of joint planes, quartz-axes, and sheets of fluid-cavities in quartz.

A foliation is visible due to parallel biotite-flakes. Longitudinal joints parallel this direction. Normal to the foliation are cross joints and the hard way. Quartz-orientation is very faint and probably unrelated to the formation of the other structures. The sheets of fluid-cavities are numerous, well defined, and parallel to the hard way.

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NOTES AND PERSONALIA

(See also pp. 48, 59, 60, 68, 107, 110, 118, and 120)

NOTES

Meteorologiske Annaler--A new meteorological publication, Meteorologiske Annaler, was inaugurated in Norway in 1942, during the German occupation. Volume 1, consisting of 19 numbers, and the first five numbers of Volume 2, have arrived in this country recently, and are listed in this issue under Bibliography: Meteorology. It is published in Oslo by the Norwegian Meteorological Institute in collaboration wtih the Institute of Theoretical Meteorology of the University of Oslo, and is edited by Th. Hesselberg and H. Solberg. Each number contains a single paper, representing an important contribution to the subject of Meteorology. The papers are in English, French, and German.

Transactions, American Geophysical Union Volume 27, Number I February 1946

SEVENTY-FIVE YEARS OF SEISMOLOGY IN THE MANILA OBSERVATORY

W. C. Repetti

H. O. WOOD [see 1 of "References" at end of paper] gives 1844 as the date of the inauguration of the Manila Observatory. This may be merely a misprint, but it is 21 years too early. Elsewhere [2] he gives 1884. (Doubtless this date relates to subsidizing by the Spanish Government as stated later in this paper.--Editor) The Manila Observatory originated with a series of meteorological observations which were commenced on January 1, 1865.

In the Observatory Reports of 1868 there is mention of the record of an earthquake by the horizontal seismoscope, and hence the installation of this pendulum was made in the period 1865-1868; the exact date was not recorded. I say "there is mention in the report of 1868;" it would probably be more accurate to say that "there was mention," for I doubt if any of those reports are still in existence in any part of the world; they no longer exist in Manila. This seismoscope was a simple pendulum having a 15-inch suspension, carrying a point in the lower surface of the bob, and the point traced its motion in lycopodium powder sprinkled on a glass plate of spherical shape. There was also a vertical seismoscope consisting of a long spiral spring terminating in a bob which pushed an indicator down a scale to show the amount of vertical motion. In the Observatory we had a trace of the mark made by the horizontal seismoscope in an earthquake of 1872, the oldest record in the Observatory. However, this was not the first pendulum in the Philippines. A very complete report was issued by the Spanish Government on an earthquake of 1851, and mention is made therein of a pendulum in operation in a town in southern Luzon, and the amplitudes of its oscillations were noted.

In July, 1880, there was a series of severe earthquakes which caused considerable damage in Manila and this aroused a new interest in seismology, and the result was an increase in instruments in the following years. The first was a BERTELLI tromometer, which was merely a long simple pendulum, protected against air-currents and provided with a scale and reading glass. Then came a CECCHI micro-seismoscope for both horizontal and vertical motions, then a ROSSI seismoscope for both motions and a CECCHI seismograph for horizontal and vertical motions. This last gave a record on smoked paper, and a good number of these were preserved in the Observatory files.

In 1884 the Observatory was subsidized by the Spanish Government as the Central Weather Bureau of the Philippines in meteorological work.

Around 1887-88 two new instruments were acquired, namely, a EWING duplex pendulum and a GRAY-MILNE three-component seismograph. The former was designed to produce a series of dots by means of an electric spark passing through paper soaked in a solution of iodine, but it does not seem to have functioned. The GRAY-MILNE had two independent horizontal pendulums, and the vertical-motion pendulum had essentially the same suspension as the modern GALITZIN-WILIP. The record was made with ink on a long roll of white paper, and a fourth pen marked seconds at one side of the record. Several of these records were preserved.

In 1890 the Sections of Seismology and Terrestrial Magnetism were officially subsidized by the Spanish Government, and this arrangement has been continued during the American regime.

There was no further instrumental advance until 1901 or 1902 when a three-component VICENTINI was purchased, and in 1907 a pair of horizontal pendulums was constructed in the Observatory. In 1910 a 1000-kg WIECHERT inverted pendulum was installed, and just prior to the outbreak of World War I steps were taken to acquire a GALITZIN vertical pendulum, but the War prevented its delivery. No further instrumental advance was made until 1930 when we installed a complete set of GALATZIN-WILIP seismometers. There is no need to describe the instruments of this century, and I refrain from descriptions of the older ones because such descriptions are never satisfactory, and adequate explanations and diagrams can be found in one of the older numbers of the Beitrage zur Geophysik. Fortunately, a few years before the War I sent to Father

MACELWANE individual photographs of each instrument, taken by Father DOUCETTE.

In a review of this kind we must make mention of the subsidiary stations. The first of these, in order of time and value, was the station in Baguio, the mountain resort city of the Philippines. The seismic equipment, installed in 1909, was a set of locally made horizontal pendulums, each having a mass of 116 pounds, and a three-component VICENTINI which had been made in Manila and installed in St. Louis in 1904 as an exhibit in the Louisiana Purchase Exposition. This last circumstance enables us to say that the Manila Observatory operated one of the pioneer seismic observatories of the United States. In 1930 the VICENTINI of the Manila Observatory was transferred to Baguio and the old St. Louis VICENTINI was retired to the seismic museum in Manila. In 1931 a 200-kg WIECHERT inverted pendulum was installed in Baguio and the horizontal pendulums were taken to Manila, renovated, improved, and substituted for the 1907 horizontal pendulums.

In 1910 a small observatory was built at Ambulong on the north shore of Lake Taal in consequence of the eruption of Taal Volcano in January of that year. The seismic equipment of this Observatory was an AGAMENNONE three-component seismograph and the 1902 VICENTINI from Manila, the latter being replaced in Manila by an improved model. These two instruments were replaced by a 200-kg WIECHERT inverted pendulum about 1938.

In 1914, at the request of the United States Navy, a 200-kg WIECHERT inverted pendulum was installed in the Governor's office in Agaña on the island of Guam. And in the same year a similar instrument was placed at Butuan on the north shore of Mindanao.

In 1917 a VICENTINI, locally made, was set up at Mambajao, Camiguin Island, off the north coast of Mindanao. This installation was made at the request of the local officials because of the proximity of an old volcano which has been dormant since 1871. No results of any value were obtained from this station, and it ceased to operate about ten years ago owing to lack of support by the local authorities.

About 1938 a 200-kg WIECHERT inverted pendulum was placed at Tagaytay Ridge, elevation 2,100 feet, overlooking Taal Lake and Volcano, and this installation was chiefly due to the suggestion of BAILEY WILLIS that a closer check be kept on Taal Volcano.

We were never able to establish an accurate time-service in any of the subsidiary stations, and hence their value was limited. Because of its location, 200 km due north of Manila, the station in Baguio was very helpful in locating epicenters in and around northern Luzon, especially in the seismic strip in the China Sea parallel to the west coast of Luzon. The station at Butuan was helpful in locating the epicenters of the Mindanao Deep, and the station at Guam enabled us to fix the epicenters of the Nero Deep.

If complete facilities were available, some interesting and valuable work on microseisms could be carried out in the Philippines. Father LEJAY of the Zikawei Observatory came to the Philippines before the War to make a gravity-survey and on reaching Aparri, at the north end of Luzon, the oscillations of the ground, due to surf set up by the northeast monsoon, were so pronounced that he had to proceed many miles up the Cagayan Valley to make his observations. He made direct readings on a small inverted pendulum. There was a small continuous microseismic motion in Manila and it became pronounced, and at times excessive, in the passage of a typhoon. As you well know, a typhoon is a cyclonic disturbance and in the case of a severe typhoon approaching Manila from the southeast there would be a section of its path in which strong northeasterly and easterly winds would strike the east coast of Luzon to the east of Manila. Strong microseisms would occur in Manila at this time. In those cases in which a typhoon moved north parallel to the east coast of Luzon, or crossed Luzon north of Manila, its center would reach a position such that the wind in the China Sea would come from the southwest and build up heavy seas against the China Sea Coast of Luzon south of Manila Bay. At these times large-amplitude microseisms would be recorded at Manila and continue until long after the typhoon had passed to the north. In one particular case, in September, 1932, a typhoon had reached Hong Kong, 600 miles northwest of Manila, when I had an opportunity to visit Corregidor at the entrance to Manila Bay, and I experienced heavy ground-swells still coming in from the China Sea, and microseisms were still large in Manila. From former experience I can say that those ground-swells were striking heavily on the China Sea Coast south of Manila Bay. From a study of several microseismic storms in Butuan I was led to associate them with strong southwest winds in the Mindanao Sea setting up swells against the west coast of the Surigao Peninsula at the northeast end of Mindanao.

I suspect that you will be more interested in hearing something of the happenings of the past three and one-half years. When the Japanese occupied Baguio they entered the Observatory, removed a large map of the Philippines from the wall, tore it in pieces and threw the pieces on the floor; perhaps this was some phase of the extension of the New Order in Greater East Asia. They carried away the theodolite, used in pilot-balloon observations, and some of the meteorological instruments, but did not disturb the seismograph. Later on, the seismograph was damaged and the glass case broken by the natives, who carried off the leveling-rods and some brass parts. The leveling-rods made very satisfactory axles for push carts. The instrument was restored to a fair working condition by the Filipinos who carried on the Observatory work in Manila during the occupation. I have not yet heard how the Observatory fared in the capture of Baguio by the Americans. I did see one item in the papers to the effect that American troops had captured Mt. Mirador, which was the site of the Observatory.

Ambulong, on the shore of Lake Taal, is an isolated place and although the Japanese entered the station at the beginning of the occupation they did not molest the seismograph, and the observer maintained it in operation until his supplies were exhausted, and the difficulties of travel prevented help from Manila. The seismograph at Butuan, on the ground floor of the observer's house, was destroyed when the town was burned during a fight between the Japanese garrison of 40 men and a guerrilla force of 1,000. The larger part of this guerrilla force was composed of irresponsible men from the adjacent provinces who were not genuine guerrillas. The seismograph at Guam was on the ground floor of the Governor's Palace, and I have recently learned from the Navy that this building was demolished in the retaking of Guam, and the seismograph shared the same fate. On Tagaytay Ridge, overlooking Lake Taal and the Volcano, the Japanese occupied the hotel and its grounds, and hence the seismograph was out of bounds for civilians and consequently out of service. A large force of American paratroops landed here to attack Manila from the south, and I have heard nothing about the hotel and the station. Incidentally, this hotel was a very attractive new structure, erected a few years before the war, and the Japanese "improved" it by demolishing the partitions between the rooms.

As to Manila, the Japanese entered the city about ten o'clock on the night of January 2, 1942, and a group came to the Observatory about three o'clock in the morning of January 3. Father SELGA met them and he was told to sit in the reception room and remain there. The Japs went down the corridor, looked out the window at the astronomical building, and sealed the door leading to the bridge which connected the two buildings. This did not cause any serious inconvenience because there was another way to the bridge through the Observatory wash-room. The Japs were under the impression that the Observatory was the property of the Philippine Government, all of which they intended to take over. By the time the puppet government was set up, the Japanese plans were more developed and they established their own observatory and radio station in the Engineering Building of the University of the Philippines. The puppet government appointed a Filipino as Director of the Observatory and he brought in some of his friends; the majority of the old employees continued their routine work, and local observations were continued. No forecasts or broadcasts of any kind were allowed, and, as a matter of fact, were impossible because of the lack of data and facilities. The Jesuit Fathers were not allowed to carry on the work of the Observatory but were interned on the premises. The Japanese visited the Observatory a number of times, examined the library very carefully and on one occasion sent about 50 books to Tokyo. They said the books would be returned in four or five months, but a statement of this kind by a Japanese meant precisely nothing. On another occasion they attempted to secure the cooperation of Fathers SELGA and DEPPERMANN and offered an insultingly low compensation of a few pesos a month; but their attempt failed completely. They were especially interested in securing any and all possible information on New Guinea and they, the Army meteorologists, seemed to be entirely ignorant of the fact that their own South Seas Bureau in Palau published meteorological reports containing observations at Port Moresby. The set of these reports which we had in Manila were at once stowed away where they could not be found.

In July 1944, all priests, nuns, and Protestant ministers of all denominations, and their families, were interned in Los Baños, about 35 miles south of Manila. At the same time, some 40 or 50 Americans who were interned in the Jesuit College, which was on the same premises as the Observatory, were sent to Santo Tomas Internment Camp; and a little later, internees in small hospitals and those out on special releases were gathered in. This was caused by the landing of the Americans on Halmahera and their threat to the Philippines.

The Japanese had threatened that if the Americans returned they would get only the ground, and in the battle of Manila they did their utmost to carry out that threat. Most of the concrete buildings and the best buildings of Manila were in the section of the city adjacent to the bay and south of the Pasig River which runs east and west, dividing the city into two parts. The business and shopping-district was on the north side of the Pasig and this section was completely demolished by the Japanese when they withdrew across the river to the south section when the Americans moved in from the north. In the old Walled City Section, also south of the Pasig, and in the remainder of the south section, the Japs fought from building to building, which made it necessary for the Americans to shell any building not deliberately destroyed by the Japanese, and the Observatory suffered the same fate as other structures in the neighborhood, that is, the University of the Philippines, the Assumption College for Girls, the Jesuit College for Boys, the Bureau of Science, the Medical School, and the Philippine General Hospital. These institutions occupied two large city blocks and represent only a small portion of the total destruction. In the internment-camp at Los Baños we could hear the heavy American shelling of the city and we could see the fires at night, but after our rescue we were not taken back to the city; there was no place available in which to house an additional 2140 people, the number from the Los Baños Camp. We were housed in the new penitentiary buildings erected at Muntinglupa, about 15 miles south of Manila, just before the War. Those few who went to Manila on special business said it was better not to see the destruction unless necessary.

No definite plans for the restoration of the Observatory have yet been made--in fact, no plans at all, and we are awaiting developments in Manila. However, we are collecting publications and reports as a nucleus of a future library and any contributions which we receive will be appreciated.

When the occupation of Manila began, I had completed a list of the deep-focus earthquakes of the Philippines, about fifteen in number, over the period 1920-40; and also a new catalogue of Philippine earthquakes covering the 300-year period, 1588-1899. This was the most complete and accurate catalogue that has been compiled, and fortunately it was preserved and saved by the family of PABLO GUZMAN, a Filipino member of the Society of Jesus.

The Observatory published a monthly mimeographed seismic report and a semi-annual printed report; these ceased in November, 1941. The GALITZIN-WILIP seismometers went out of service in September, 1942, when the photographic paper and developing solutions were exhausted. The WIECHERT was still in operation in July, 1944, but I do not know how much longer.

And so, with seismology beginning in the Manila Observatory in the late sixties of the last century, however crudely in the light of modern seismology, and ending in the early forties of this century, our title of "75 years of seismology" is sufficiently accurate.

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WINTER MICROSEISMS

Leonard M. Murphy

Abstract--Barometric lows over large bodies of water produce the maximum microseisms which decrease with increase in distance from the storm area. Tropical hurricanes, as well as winter storms, may be roughly traced by changes in amplitudes as the storms approach the stations in their paths. Geological units seem to have considerable influence on microseismic amplitudes. Local barometric pressure changes have no influence on the microseisms of nearby stations. Storms over land which seldom have deep lows do not produce appreciable microseisms on ordinary teleseismic records. Although such records yield valuable information on microseisms, they are not adequate for a complete study of these phenomena.

A study is being made of the correlation of low barometric pressures over land and ocean areas with microseismic amplitudes obtained at twelve stations in the United States, Alaska, Greenland, Bermuda, and Puerto Rico, shown in Figure 1. The periods covered are October, 1942, through March, 1943; October, 1943, through March, 1944; and October, 1944, through March, 1945.

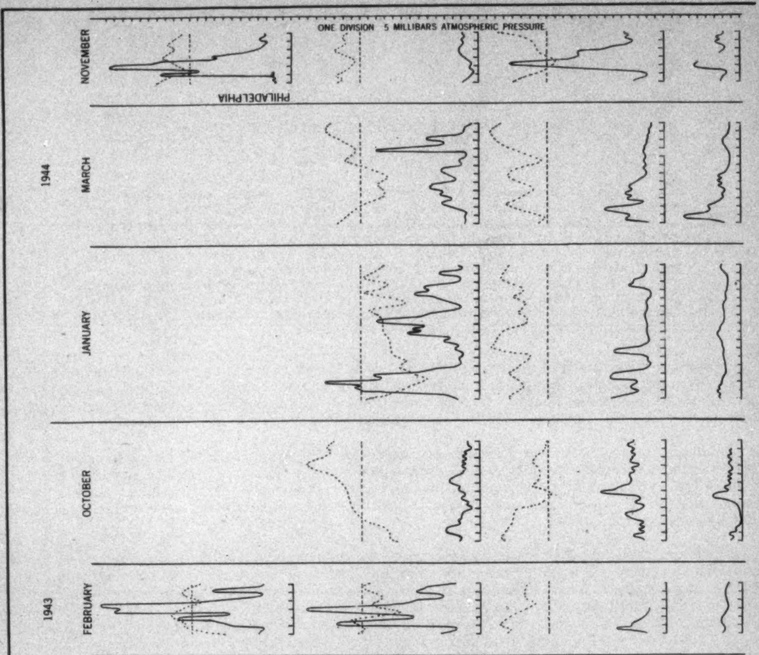
In making this survey the relative amplitudes of the microseisms recorded on the east-west component are correlated with the low pressure areas in the vicinity of the stations and all of the lows off the Atlantic and Pacific coasts, Canada, and Greenland (see Table 1). With a knowledge of the number of lows which exist each day, it is evident that the analysis becomes rather complicated.

The most important fact in the correlation of the microseisms and the lows is that the largest amplitudes occur at all of the stations when the lows are over large bodies of water as shown in Figure 1. An analysis of the intensity and width of the low areas shows that they are definitely related to the amplitudes of the microseisms. These amplitudes also decrease with increase in the distance from the storm area. A typical illustration of this latter point is the storm of November 21, 1944, off New England. This storm was recorded possibly as far west as Bozeman, Montana, with ground displacements of .012 mm at Philadelphia, .005 mm at Chicago, and .004 mm at St. Louis and Bozeman.

In the case of tropical hurricanes it is possible to follow the path of the storm by studying the increase in the amplitudes as the storm approaches the stations in its path. These phenomena are also true with regard to the path of any winter microseisms although the problem is much more complex because there may be more than one low area, simultaneously, affecting the same stations. Here, as in the case of teleseismic work when two quakes occur approximately the same time, it is necessary to study the records from the stations nearest the storm centers and associate them with the decrease in the microseisms at the more remote stations.

Deep lows off New England and Nova Scotia, which are well recorded throughout most of the United States, have no influence on the Greenland stations. The storm off the New England coast on October 18, 1942, which was recorded possibly as far as St. Louis and Bozeman, has no correlation with the microseisms at Scoresbysund. When the lows around the southern part of Greenland and in the Baffin Bay area are recorded exceptionally well in Greenland, no influence is recognized on the records in this country. On January 11, 1943, there was a low south of Greenland showing good microseisms in Greenland, but no microseisms on the continent.

There appears to be very little relation between the amplitudes of the microseisms at any particular station and low pressure areas in the immediate vicinity as may be noted in most of the cases shown in Figure 1. An exception to this fact may be the storm of January 22, 1943. A low appeared over northwest United States and moved eastward, apparently causing the microseisms at Bozeman, Montana, to increase. However, there may be some doubt in this interpretation since another low appears off Newfoundland at the same time.


1942
OCTOBER
NOVEMBER
DECEMBER
1943
JANUARY
FEBRUARY
OCTOBER
1944
JANUARY
MARCH
NOVEMBER
ONE DIVISION 5 MILLIBARS ATMOSPHERIC PRESSURE
ONE DIVISION 1 MM TRACE AMPLITUDE
PHILADELPHIA
SCORESBYSUND
IVIGTUT
WESTON
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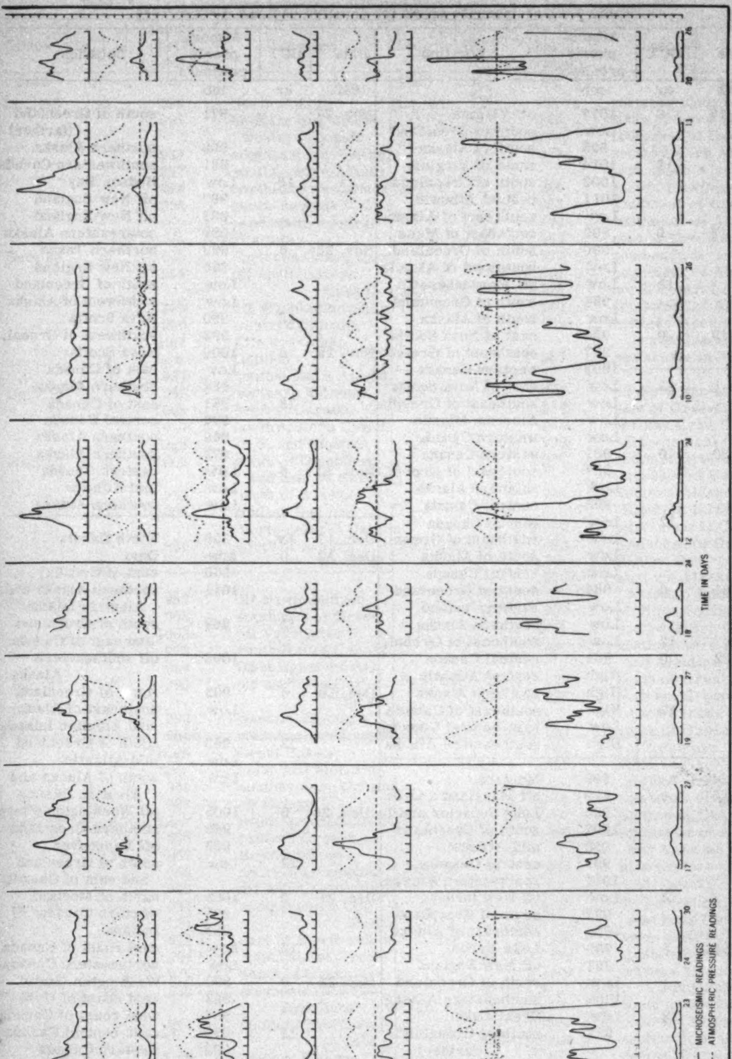

Fig. 1--Magnitude of microseisms and variation in atmospheric pressure at selected stations and periods in 1942 to 1944

Table 1--Low pressure areas for selected periods, 1942 to 1944

Date	GCT	Atmospheric pressure	Location
1942	hr	mb	
Oct. 17	0	1017	off Virginia
		Low	south of Greenland
		993	south of Alaska
	12	1014	south of Virginia
		1002	south of Greenland
		1011	central Atlantic
		Low	southwest of Alaska
Oct. 18	0	999	southeast of Mass.
		990	south of Greenland
		Low	southwest of Aleu.Is.
	12	Low	off Massachusetts
		984	south of Greenland
		Low	south of Alaska
Oct. 19	0	984	east of Nova Scotia
		987	southeast of Greenl.
		1002	western Canada
	12	Low	east of Nova Scotia
		Low	southeast of Greenl.
		Low	Aleutian Islands
		Low	western Canada
Oct. 20	0	981	eastern Canada
		987	southeast of Greenl.
		Low	southern Alaska
		996	central Canada
	12	Low	east of Canada
		Low	southeast of Greenl.
		Low	south of Alaska
		Low	central Canada
Oct. 21	0	984	south of Greenland
		Low	eastern Iceland
		Low	southern Alaska
	12	Low	southeast of Greenl.
Oct. 22	0	981	central Canada
		High	central Atlantic
		High	southern Alaska
	12	High	southeast of Canada
		Low	east-central Canada
		High	southeastern Alaska
Nov. 24	Av.	999	Montana
Nov. 25	6	999	off Maryland and Del.
		996	Lake Superior and Ia.
		1002	south of Greenland
		990	mid-Atlantic
		993	central Canada
		1011	southeastern Alaska
	18	Low	off New Jersey
		987	south of Greenland
		1014	southeast of Alaska
Nov. 26	6	990	Lake Huron
		993	off New England
		Low	south of Greenland
		1005	southeastern Alaska
	18	Low	Great Lakes
		981	south of Greenland (farther)
Nov. 27	6	993	north of Great Lakes
		990	Hudson Bay
Nov. 27		971	south of Greenland (farther)
		999	southern Alaska
		991	southwestern Canada
	18	Low	Hudson Bay
		987	off New England
		987	off New England
		1002	southeastern Alaska
Nov. 28	6	999	northern Texas
		996	off New England
		Low	south of Greenland
		Low	southwest of Alaska
	18	990	Nova Scotia
		993	southwest of Greenl.
Nov. 29	6	1009	Nova Scotia
		Low	east of Canada
		984	southern Alaska
	18	981	east of Canada
		996	central Canada
		969	southern Alaska
		972	southern Alaska
Nov. 30	6	Low	eastern Canada
		Low	mid-Atlantic
		Low	southern Alaska
Dec. 17	Av.	999	North Dakota
Dec. 18	0	Low	Ohio
		960	east of Canada
		1011	southern Alaska and Aleutian Islands
	12	969	south of Greenland and east of Canada
		1008	off southeastern Alaska
Dec. 19	0	963	south of Greenland
		Low	southeast of Alaska and Aleutian Islands
	12	963	south of Greenland
		Low	mid-Atlantic
		Low	south of Alaska and Aleutian Islands
Dec. 20	0	1005	off Washington (State)
		945	southern Greenland
		993	off Vancouver
	12	Low	south of Greenland and east of Canada
Dec. 21	0	1005	north of Montana
		993	western Canada
		983	Indiana
	12	Low	east coast of Canada
		Low	northeastern Canada
Dec. 22	0	993	Washington (State)
		983	east coast of U. S.
		987	west coast of Canada
	12	999	east-central Canada
		990	western Canada
		High	north-central U. S. and central Canada

Table 1--Low pressure areas for selected periods, 1942 to 1944 (continued)

Date	GCT	Atmospheric pressure	Location
1942	hr	mb	
Dec. 23	0	999	North Dakota
		993	Montana and southwestern Canada
		987	southeastern Alaska
	12	997	southeastern Alaska
		996	northeastern Canada
		996	north-central U. S. and south-central Canada
Dec. 24	0	1005	northern Great Lakes
		999	off northeastern Canada
		996	off Washington (State)
		990	western Canada
		High	Atlantic Ocean
	12	Low	Ontario
		987	southeastern Alaska
Dec. 25	0	996	northern Montana
		1029	central Canada
		1017	northwestern Canada
	12	High	U. S. and Canada
Dec. 26	0	1005	south of Greenland and east of Canada
		993	south of Alaska
	12	1005	Hudson Bay and north-central Canada
		984	south of Alaska (farther)
1943			
Jan. 20	0	993	off Newfoundland
		980	southeast of Greenl.
		1002	off Vancouver
	12	975	southeast of Canada
		998	Washington (State)
Jan. 21	0	993	off northern California
		990	western Montana
		951	southeastern Canada
		High	Great Lakes
		Low	Idaho and Montana
	12	965	southeastern Canada
		987	off Oregon
Jan. 22	0	Low	southeastern Canada
		978	eastern Oregon
	12	969	Newfoundland
		960	south of Greenland
		993	off Washington (State)
Jan. 23	0	984	northeastern California
		978	east of Newfoundland
		984	southeast of Greenl.
		975	south of Greenland
	12	972	northeast of Newfoundland
		972	south of Newfoundland
		Low	eastern Oregon
1943	hr	mb	
Jan. 24	0	996	northern Colorado
		966	south of Greenland
	12	Low	southeast of Greenl.
		975	southwestern Alaska and upper Aleutian Is.
Jan. 25	0	996	east of Newfoundland
		966	southeast of Greenl.
		981	southwest of Alaska
	12	993	east of Newfoundland
		972	southeast of Greenl.
		981	southwest of Alaska
Jan. 26	0	993	north-central Atlantic
		989	southwest of Alaska
	12	999	between Greenland and Canada
		987	southeastern Alaska
Feb. 18	0	990	off Nova Scotia
		984	east of Greenland
		993	northwestern Canada
		999	north-central Canada
	12	987	south of Greenland and east of Canada
		984	western Alaska and Aleutian Islands
		999	west-central Canada
Feb. 19	0	978	southeast of Greenl.
		Low	Hudson Bay
		975	western Alaska and Aleutian Islands
	12	999	off Nova Scotia
		Low	southwestern Greenl.
		Low	southwestern Alaska and Aleutian Islands
Feb. 20	0	999	north of Great Lakes
		996	between Greenland and Canada
		984	south of Greenland
		991	northwestern Canada
	12	993	north of Great Lakes
		Low	south of Greenland
		Low	southeast of Greenl.
		Low	northwest Canada
		990	southwest of Alaska and Aleutian Islands
Feb. 21	0	975	between Greenland and Canada
		Low	St. Lawrence and northern New York
		993	west-central Canada
	12	984	southeast of Greenl.
		Low	between Greenland and Canada
Feb. 22	0	990	south of Greenland
		Low	central Canada
	12	Low	southeast of Greenl.
		999	central Canada

Table 1--Low pressure areas for selected periods, 1942 to 1944 (continued)

Date	GCT	Atmospheric pressure	Location
1943	hr	mb	
Feb. 22		993	southwestern Aleutian Islands
Feb. 23	0	999	Wisconsin
		973	east of Greenland
		Low	eastern Canada
		Low	southwestern Aleutian Islands
Oct. 14	0	987	Lake Superior
		Low	east of Nova Scotia
	12	981	north of Great Lakes and south of Hudson Bay
		984	north of Great Lakes and south of Hudson Bay
		Low	northern Texas and southern California
Oct. 15	0	978	near Hudson Bay
		963	southwest of Alaska
	12	975	near Hudson Bay
		Low	southwestern Alaska
		Low	southern California
Oct. 16	0	1002	Pennsylvania and Maryland
		Low	east of Canada
		981	southwestern Alaska
		1005	north of Puerto Rico
	12	990	southeastern Alaska
		984	northeastern Canada
Oct. 17	0	993	Lake Erie
		993	southeastern Alaska
	12	990	southeastern Alaska
		Low	Oregon
Oct. 18	0	987	north of Great Lakes
		990	Aleutian Islands
	12	993	north of Great Lakes
		Low	south of Alaska (farther)

A hurricane developed east of the Lesser Antilles on October 11 and passed Puerto Rico about midnight on the 14th. At noon on the 16th it was 12° east of Florida. By noon of the 17th it was 3° east of Boston and shortly dissipated in Maine.

Date	GCT	Atmospheric pressure	Location
1944	hr	mb	
Jan. 10	0	950	off eastern Canada
		1005	north-central Canada
	12	970	south of Greenland and east of Canada
Jan. 11	0	1010	north of Great Lakes
		965	south of Greenland
		970	southwest of Alaska
	12	1010	north of Great Lakes
		965	south of Greenland
		980	southwest of Alaska
Jan. 12	0	1010	north of Great Lakes
		960	southeast of Greenl.
		980	southwestern Alaska and Aleutian Islands
	12	950	southeast of Greenl.
		1005	east of Canada
		Low	western Canada
Jan. 13	0	Low	eastern Canada
		Low	northwestern Canada
	12	980	eastern Canada
		990	central Canada
Jan. 14	0	970	south of Greenland
		960	Aleutian Islands
		Low	between Greenland and Canada
	12	960	southeast of Greenl.
		Low	northeast of Canada
Jan. 15	0	Low	between Greenland and Canada
		Low	southwestern Aleutian Islands
		Low	Pacific Ocean, west of United States
	12	Low	between Greenland and Canada
Jan. 20	0	1000	off New England
	12	Low	off Nova Scotia
		Low	off northeastern Canada
Jan. 21	0	996	Lake Superior
		950	off Maryland
		Low	northeastern Canada
	12	852	east of Maryland
		Low	off Nova Scotia
Mar. 1	0	996	off New England
		995	off Maryland
		Low	northeastern Canada
		1005	off California
	12	985	east of Maryland
		Low	off Nova Scotia
Mar. 2	0	975	off Nova Scotia
		1005	off Vancouver
	12	970	off Nova Scotia
		1005	off Vancouver
Mar. 3	0	1002	New Mexico
		970	off Nova Scotia
		1000	off Vancouver
		995	between Greenland and Canada
Mar. 4	0	960	off Newfoundland
		990	Missouri
		1000	off Washington (State)
	12	970	east of Newfoundland
		1000	Washington (State)
Mar. 5	0	970	northeast of Newfoundland
		995	far Pacific off U. S.

Table 1--Low pressure areas for selected periods, 1942 to 1944 (continued)

Date	GCT	Atmospheric pressure	Location
1944	hr	mb	
Mar. 5		Low	west of Alaska
	12	975	northeast of Newfoundland
Mar. 6	0	980	east of Newfoundland
		980	off southeastern Alaska
	12	980	east of Newfoundland
		980	off southeastern Alaska
Mar. 7	0	984	Lake Superior
		985	south of Greenland and east of Canada
		Low	Pacific Ocean off Canada
	12	990	north of Great Lakes
		984	south of Greenland
		972	south of Alaska
Mar. 8	0	996	north-central Great Lakes
		995	west of Greenland
		970	south of Alaska
	12	985	east of Canada
		990	off southeastern Alaska
Mar. 9	0	985	eastern Canada
		985	southeastern Alaska
	12	980	eastern Canada
Mar. 10	0	1000	southeastern Canada
		999	northern Montana
		Low	west-central Canada
	12	1000	between Greenland and Canada
		985	central Canada
Mar. 11	0	1002	northern North Dakota
	12	Low	mid-Atlantic
Mar. 12	0	1005	Great Lakes
		1010	east of Nova Scotia
		965	southwestern Aleutian Islands
	12	1015	east of Newfoundland
		950	northeastern Canada
Mar. 13	0	1011	off Virginia
		970	southwestern Aleutian Islands
		995	northeastern Canada
	12	975	southwestern Aleutian Islands
1944	hr	mb	
Nov. 20	0	975	west of Canada
		1005	between Greenland and Canada
		1010	northwestern Canada
	12	980	south of Alaska
		Low	northwestern Canada
		Low	east of Newfoundland
		Low	between Greenland and Canada
Nov. 21	0	999	off New Jersey
		Low	south of Alaska
		Low	Hudson Bay
	12	995	off New York
		1000	west-central Canada
Nov. 22	0	987	off Massachusetts and Rhode Island
		995	southeastern Alaska
	12	985	off New England
		990	south of Alaska
Nov. 23	0	985	off New England (farther)
		1005	south of Alaska
		1000	Hudson Bay
	12	1000	off Washington (State)
		Low	between Iceland and Greenland
		Low	off New England
Nov. 24	0	999	western Montana
		990	off New England
		Low	southwestern Aleutian Islands
		Low	between Greenland and Canada
	12	1000	off Nova Scotia
		Low	Hudson Bay
		990	southwestern Aleutian Islands
Nov. 25	0	990	off New England (farther)
		990	off western Canada
		970	southwestern Aleutian Islands
		990	central U. S.
	12	995	central U. S.
		985	off New England (farther)
		990	off western Canada
		990	southwestern Aleutian Islands

If the local storm occurs over the sea and near the coast, there is a considerable increase in the amplitudes of the microseisms at a coastal station in the immediate vicinity of the storm. Very good examples of this are the Weston and Harvard stations which have well defined microseisms for these local storms. It may also be that the periods of such microseisms are usually quite short.

At San Juan there is often very little change in local barometric pressure and rather large microseisms appear on the records. In such a case a low over the ocean may be found in the vicinity of the island.

Because there are so few seismic stations in north-central Canada and there are so many lows in that region, it is very difficult to establish any correlation between lows and the microseisms. It will be necessary to obtain much more microseismic data before anything definite can be stated. This is especially true in the Hudson Bay region.

It has been found in some instances, as in the storm of January 11, 1943, over the Great Lakes, that the microseisms do not seem to be transmitted to any great distance. This is probably due to the fact that the storms do not have very deep lows and that they are not over oceanic bodies of water.

Along the northeast coast of the United States there seems to be some delay in the recording of the maximum of the microseisms after the minimum pressure area has developed over the ocean. This may be directly due to the response of the instruments. In a recent investigation, in which the seismographs were more favorably adapted to the recording of microseisms than the regular teleseismic instruments, it was found that the former responded with a quick build-up of amplitudes many hours ahead of the latter. The fact is that the actual ground-motion cannot be computed with the necessary accuracy from many types of teleseismic instruments.

At the present time one of the difficult problems involves the separation of storms in different regions simultaneously affecting the same station. With the scarcity of teleseismic stations throughout the continent which are adequately equipped with instruments to record well-defined microseisms, it often becomes difficult to recognize the source of the microseisms. If it were possible to determine an azimuth for them at each station, this difficulty would be eliminated. Until now the only successful means for determining the azimuth is the tripartite type station developed by J. B. MACELWANE and J. E. RAMIREZ.

Knowing the azimuth of storms, it would be possible to determine their origin from two or more tripartite stations, assuming that the direction of wave propagation was a true indication of the direction of the storm. This has been a very controversial question, especially since one school of seismologists advances the theory that microseisms are caused by surf.

The present investigation is clarifying our ideas regarding what factors control the amplitudes of microseisms, and it is therefore a desirable, even a necessary, supplement to the directional investigations which have been made. It is also intended to reveal to what extent we can count on ordinary seismographic stations to help locate low pressure areas. The conclusion seems to be that, up to a certain point, storm locations can be roughly estimated from ordinary teleseismic stations, and that the outlook might be excellent if the right kind of instruments were operated in certain critical areas. The investigation is also yielding important information on some controversial theories regarding the propagation of microseisms over continental areas.

The author wishes to express his appreciation to all who have assisted in making the above data available, and especially to FRANK NEUMANN of the United States Coast and Geodetic Survey for his many thoughtful suggestions, and to the United States Weather Bureau for the meteorological data.

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DURATION-FREQUENCIES OF LOW CEILINGS IN CLIMATOLOGY

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Abstract--The parallel growth of weather information for the special benefit of aviation and the use of punched-cards in climatology is discussed, with the notation that very little use, in a climatological sense, had been made of the weather data designed for aviation until the beginning of World War II. The various types of climatic summaries in common use are described, and it is noted that they are not particularly well adapted to airways weather information, such as ceilings and visibility. By the use of punched-card methods of machine tabulation, special and more complex types of climatic summaries are available. The use of duration frequencies of the limiting categories of airways weather data is considered to more closely approximate the operational needs of aviation and other interests than any other type of summary.

The first use of ceiling data in the United States was made about twenty years ago, accompanying the establishment of organized weather service for the benefit of aviation along the commercial airways in the middle 20's. The phrase "for the benefit of aviation" describes and limits the concept of a ceiling which may then be defined as a convenience for practical use, which is determined by the height of the base of clouds above the surface in amounts which appear to an observer in a given locality to cover half or more of the sky. From this definition of a ceiling, it follows that the use of information on ceilings is limited to the specific field for which the convenience was designed (aviation).

The immediate uses of ceiling information are well known. Over a given locality it determines the level at which contact flight can be maintained. Along a given airway the lowest ceilings determine whether or not contact flight is possible. The airway forecaster makes use of ceiling data for short range forecasts. The accurate reporting and forecasting of ceiling heights at levels which determine whether or not an airport will remain open to air traffic become very important factors in the economic operations of commercial aviation.

"What use can be made of the accumulated ceiling data?" is a question that has been asked very frequently. A number of studies of local conditions in respect to the occurrence of low ceilings have been made, but in every case the investigator has been limited by the time available for hand tabulations. This has proved inadequate, usually, to handle the bulk of the material. Ceiling measurements are recorded every hour of the day--8760 observations in the course of a year at a single station. Since there are 755 stations in the United States and possessions making such hourly observations, a total of 6,613,800 ceiling observations are accumulating yearly. If we assume that ten years is the minimum period for which reliable means may be computed, then there are 87,648 observations to be tabulated and summarized for each station. It is no wonder that studies making use of ceiling data or similar 24 hourly data have been few in number and limited in extent. The volume of the data has been too great to be handled by methods of hand tabulation.

Coincident with the development of the airways weather reporting system and the accumulation of hourly weather data, there has been a development of methods of machine tabulation, commonly known as the punch card methods. Punch card methods of tabulating and sorting meteorological data were first used in England in 1921 and on the continent of Europe in 1927. In the United States, the system was used by W. F. McDONALD in the early 30's to summarize a vast accumulation of marine meteorological observations. This was one of the outstanding WPA projects, the results of which advanced our knowledge of marine climatology and have been of incalculable benefit in the prosecution of the present World War.

The need of summarizations of our airways weather data was recognized by the Weather Bureau in the late 30's and two projects were undertaken which have also proved to be of considerable value in promoting the efficiency of the war effort. The first project was the summarization of basic ceiling, visibility, and other airways weather data in the form of percentage frequency tabulations (see Figs. 1, 2, and 3). The second was the summarization of airways weather data for

selected stations, particularly ceiling, visibility, and wind-data in the form of an Atlas of Airways Weather (Fig. 4). These projects were also undertaken as WPA projects. Certain summarizations in the form of frequency tabulations have been continued under the auspices of the Weather Division, United States Army Air Forces, since the closing of the WPA projects.

In addition to the three major projects mentioned, the Weather Division of the United States Army Air Forces has made extensive and continuous use of methods of machine tabulations of weather data, the discussion of which must be postponed until after the close of the war. But it may be said here that the projects are conclusive evidence that great quantitites of meteorological data can be handled efficiently and effectively by the use of IBM tabulating and computing machines.

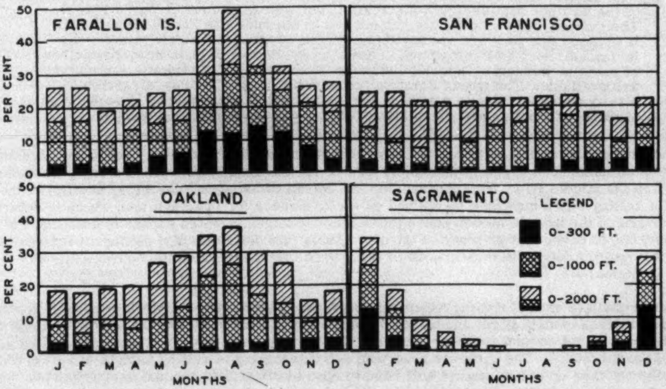

Fig. 1--Mean monthly frequency of low ceilings at selected stations

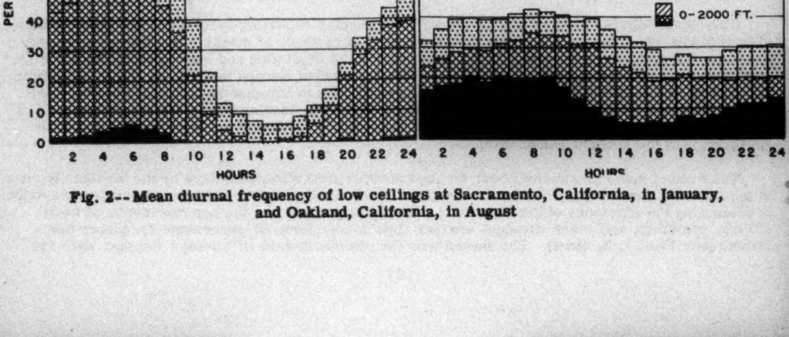

Fig. 2--Mean diurnal frequency of low ceilings at Sacramento, California, in January, and Oakland, California, in August

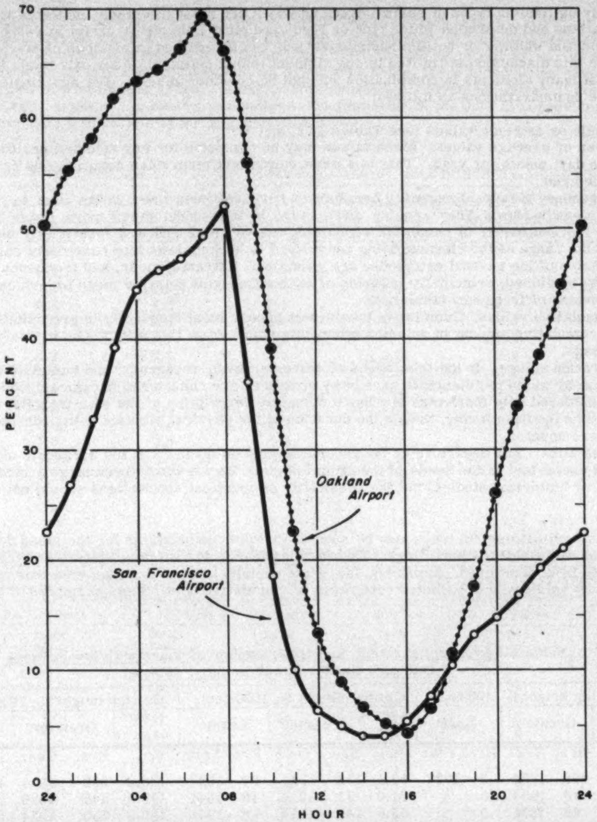

Fig. 3--Diurnal frequency of low ceilings (0 to 2,000 feet) at the Oakland and San Francisco airports in August

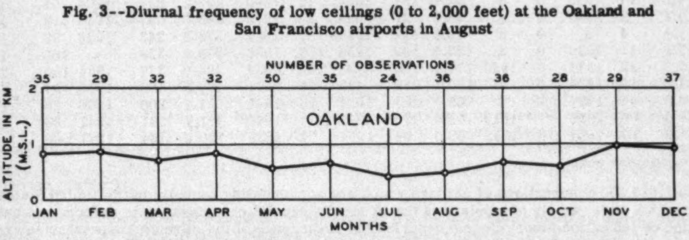

Fig. 4--Mean height of stratus clouds at Oakland, California

We may outline the types of summarizations which are most commonly available in climatological publications and determine which type or types are most suitable or useful in respect to ceiling information, and whether or not the summarizations can be adapted to methods of machine tabulation. Since this discussion is limited to one element (cloud ceilings), other extremely interesting problems of many elements in combination will not be considered here. For any single element we may desire summarizations as follows:

(1) Single or extreme values (see Tables 1, 2, and 3).

(2) Mean or average values. Mean values may be computed for any selected period of time, such as the day, month, or year. This is a most convenient term when comparisons between stations are desired.

(3) Frequency values. Frequency breakdowns have not been used in the past to the same extent as mean values. They require more labor in tabulating; much more space in publications; are more difficult to handle in climatological writings and are less easily understood. Ordinarily the range of the element being considered is broken down into convenient categories and the frequencies of the several categories are compiled. Extreme, mean, and frequency data may be variously combined; principally in terms of (a) frequency of selected mean or extreme categories or (b) the means of frequency tabulations.

(4) Cumulative values. Cumulative tabulations appear most frequently in precipitation data, where the cumulative amount in selected intervals of time from five minutes up to one year are in common usage.

(5) Duration values. In the tabulations of extreme, mean, frequency, and cumulative values, the divisions by which the elements have been measured are considered paramount; the time element is considered only incidental to a more complete description of the element. But under certain conditions the time factor, that is the duration of the physical element being considered, becomes paramount.

(6) Anomalies. The departure of the recorded value or mean from the normal is often a convenient and useful tool in the hands of the climatologist. Its uses have been largely confined to theoretical or historical studies, but the possibility of practical applications should not be overlooked.

These six climatological tools may be used in various combinations for the more detailed descriptions of comparative climatology. The combinations of the extreme, mean, and frequency data have already been mentioned. Similarly, there are combinations of duration with extreme, mean, and frequency values and of selected categories of cumulative data. Some examples of these will be given later.

Table 1--Average, greatest, and least number of hours with low ceilings at Oakland, California, by months, 1934-41

Month	Ceiling height 0 - 300 feet					Ceiling height 0 - 1000 feet					Ceiling height 0 - 2000 feet				
	Average	Greatest		Least		Average	Greatest		Least		Average	Greatest		Least	
	Hrs.	Hrs.	Year	Hrs.	Year	Hrs.	Hrs.	Year	Hrs.	Year	Hrs.	Hrs.	Year	Hrs.	Year
Jan.	20.3	66	1934	2	1937	55.1	133	1934	27	1937	128.3	238	1934	82	1937
Feb.	7.8	18	1934	0	a	31.0	52	1934	10	1941	113.5	145	1936	58	1941
Mar.	10.9	62	1934	0	a	53.5	141	1934	2	1941	128.9	250	1934	54	1941
Apr.	4.6	14	1939	0	a	57.4	137	1934	16	1940	152.5	231	1934	91	1940
May	0.4	2	1940	0	a	63.1	128	1934	28	1936	190.0	237	1939	118	1937
June	1.4	4	a	0	a	79.8	122	1934	35	1941	173.2	243	1938	99	1936
July	3.9	11	1938	0	a	153.0	199	1938	107	1936	270.8	328	a	160	1936
Aug.	6.6	22	1934	0	1940	177.4	280	1934	105	1938	284.0	377	1934	190	1937
Sep.	4.6	10	1938	0	a	100.1	279	1935	29	1941	190.3	402	1935	134	1939
Oct.	16.0	47	1937	1	a	63.9	125	1937	26	1941	127.4	200	1936	76	1939
Nov.	25.0	90	1936	1	1938	61.6	137	1941	11	1940	111.1	191	1941	35	1938
Dec.	33.2	67	1937	8	1935	65.0	94	1937	21	1935	120.6	164	1941	66	1935

a More than one year.

The 6,613,800 observations of ceilings which are accumulating annually in the United States permit such a wide variety of tabulations that it merits careful consideration to determine what tabulation or tabulations most clearly describe the occurrence of the element and what ones are of the most practical use. It is at once apparent that extreme values of ceiling have little or no value.

The mean height of the base of selected types of clouds has been used (Fig. 4), however, and may be considered a special application of ceiling data, but the frequency of selected categories of ceiling heights is obviously a more useful tabulation. Since the period of record varies and the time interval of the original observations is not always the same, these frequencies have most often been given in percentages (Figs. 1 and 2). This provides a convenient means of comparison between stations. Besides the mean frequencies the compilation of the data also provides information on the extreme occurrence of the selected categories.

Table 2--Average duration of low ceilings at Oakland and Sacramento, California

Month	Oakland (1934-1941)			Sacramento (1934-1939)		
	Height of ceiling			Height of ceiling		
	0 - 300 feet	0 - 1000 feet	0 - 2000 feet	0 - 300 feet	0 - 1000 feet	0 - 2000 feet
	hrs	hrs	hrs	hrs	hrs	hrs
January	4.2	3.3	4.7	7.1	8.2	8.3
February	3.3	3.2	3.8	4.5	5.6	5.8
March	4.6	4.2	5.1	2.1	3.1	4.8
April	2.8	4.5	5.0	3.0	2.5	3.7
May	1.0	4.2	6.2	2.7	2.2	2.8
June	1.6	5.4	5.8	0.0	2.8	3.1
July	2.2	6.2	8.3	0.0	2.3	2.8
August	3.3	5.8	8.7	0.0	1.3	1.8
September	2.6	5.8	7.2	0.0	1.8	3.8
October	3.8	5.0	5.3	2.9	3.1	2.9
November	5.3	5.4	5.4	3.9	3.7	4.5
December	4.8	4.1	4.9	5.9	7.5	8.3

Table 3--Maximum duration of low ceilings at Oakland and Sacramento, California

Month	Oakland (1934-1941)			Sacramento (1934-1939)		
	Height of ceiling			Height of ceiling		
	0 - 300 feet	0 - 1000 feet	0 - 2000 feet	0 - 300 feet	0 - 1000 feet	0 - 2000 feet
	hrs	hrs	hrs	hrs	hrs	hrs
January	13	20	43	37	128	128
February	13	19	29	22	87	88
March	13	18	110	7	13	36
April	9	18	40	9	20	35
May	1	16	45	3	5	11
June	3	16	59	9	9	11
July	7	18	42	0	5	8
August	10	21	61	0	2	2
September	7	18	44	0	4	17
October	12	21	36	6	8	9
November	17	37	37	12	15	30
December	22	39	39	33	110	110

There are also the diurnal distribution of ceiling data for stations for which hourly observations are available (Fig. 3). These are given for the same categories, and similar types of summaries are available, that is, the mean and extreme occurrence of selected categories of ceiling heights on a diurnal basis. It is also possible to express the results obtained from the hourly readings in terms of total hours per month of the selected categories, both in mean and extreme values. The latter include the greatest and least number of hours of occurrence in the selected categories (Table 1).

The question may still be raised as to whether or not we have made the most useful tabulations of ceiling data. While the original purpose of ceiling measurements was "a convenience for the benefit of aviation," the climatological data on ceilings may be used in several ways: It may be used to determine (a) those schedules having the least interference from low ceilings; (b) the best

location for terminal facilities; (c) the need and location of alternate terminals; (d) the type of equipment necessary for efficient operation; (e) in the case of private flying, the choice of airfield sites, the selection of locality and time for various activities, the planning of vacation flying, etc.; and (f) comparisons of the operating efficiency of airlines and their terminals.

Table 4--Average number of occurrences of different durations of low ceilings at Oakland and Sacramento, California

Durations hrs	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Oakland (1934-1941)												
Ceiling 0 - 300 feet												
Over 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Over 12	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.8
Over 6	1.2	0.3	0.6	0.1	0.0	0.0	0.1	0.1	0.1	0.6	1.7	1.6
Over 2	2.1	0.7	1.4	0.5	0.0	0.2	0.5	1.0	0.5	2.1	2.6	3.8
Total occur.	4.9	2.4	2.4	1.6	0.4	0.9	1.8	2.0	1.8	4.3	4.5	6.9
Ceiling 0 - 1000 feet												
Over 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Over 12	0.9	0.8	0.9	1.0	0.8	1.8	3.2	3.8	2.5	1.8	1.1	1.2
Over 6	2.8	1.0	2.9	3.2	3.7	5.2	11.1	11.3	6.9	3.3	3.6	2.4
Over 2	5.4	2.9	6.4	7.1	7.8	8.3	17.0	18.4	9.9	7.1	6.6	5.4
Total occur.	16.5	9.8	12.9	12.9	14.9	14.9	24.9	30.8	17.4	12.8	11.4	15.8
Ceiling 0 - 2000 feet												
Over 24	0.5	0.2	0.1	0.2	0.4	0.2	0.5	0.8	0.5	0.1	0.4	0.6
Over 12	3.3	1.4	2.3	3.1	4.5	4.1	7.9	9.2	5.3	2.6	2.0	2.1
Over 6	5.5	5.6	7.3	8.5	10.7	9.9	17.7	17.8	12.9	7.1	5.6	6.1
Over 2	12.5	13.5	13.2	17.0	18.8	17.3	24.3	23.8	16.8	13.5	10.7	11.9
Total occur.	27.5	29.8	25.5	30.4	30.9	30.0	32.8	32.6	26.5	24.1	20.5	24.4
Sacramento (1934-1939)												
Ceiling 0 - 300 feet												
Over 24	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Over 12	2.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5
Over 6	5.4	1.6	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.8	5.3
Over 2	8.1	3.3	0.8	0.7	0.3	0.0	0.0	0.0	0.0	1.0	2.6	10.0
Total occur.	13.8	7.2	4.0	1.3	0.5	0.0	0.0	0.0	0.0	2.0	4.9	17.7
Ceiling 0 - 1000 feet												
Over 24	1.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Over 12	3.8	1.8	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.9
Over 6	6.1	2.5	1.2	0.4	0.0	0.2	0.0	0.0	0.0	0.3	1.8	7.1
Over 2	12.1	6.5	3.5	1.2	1.0	0.2	0.2	0.0	0.3	1.8	3.8	11.6
Total occur.	20.8	15.0	10.0	5.8	2.8	0.8	0.5	0.5	1.7	4.0	9.8	20.3
Ceiling 0 - 2000 feet												
Over 24	2.2	1.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.5
Over 12	5.4	2.3	1.4	0.3	0.0	0.0	0.0	0.0	0.2	0.0	1.0	3.5
Over 6	8.6	5.5	3.9	1.6	0.2	0.3	0.2	0.0	0.2	0.5	3.0	7.7
Over 2	15.6	13.5	7.9	4.6	2.5	1.0	0.2	0.0	1.0	2.8	5.8	13.2
Total occur.	27.2	24.5	16.0	11.7	5.3	2.5	0.8	0.7	2.2	6.8	12.2	22.0

The needs of commercial airlines (as well as the private aviation enthusiast) in respect to climatological data may be summed up in the question "How often and for what periods of time will our operations be interfered with by the Weather?" "How often" suggests frequency tabulations. "For what periods of time" suggests duration tabulations (Tables 2 and 3). These tabulations may be combined into a single tabulation of duration-frequency of selected categories of ceiling heights (Table 4). Duration-frequencies are expressed in terms of extreme and mean occurrences of monthly and annual values. It is thought that duration-frequencies, together with hourly frequency summarizations, most nearly approximate the needs of the aviation interests in the field of climatological statistics.

Techniques for the evolving of duration-frequencies by means of IBM machines were perfected by **LESLIE SMITH** of New Orleans, and a few notes on the procedures may be of interest. (a) The categories to be used are predetermined and the selection of the categories from the cards is made by the sorting machine. (b) With all the cards in the selected categories in hand they are listed on the "recap" sheets, showing the date, the hour of beginning and ending, and the duration of all occurrences in the selected categories. (c) The data are then rearranged to give the total number of occurrences in the different duration periods; total or mean values are computed. (d) Other pertinent data are immediately available. They include:

(1) The total hours of the selected category (Table 1).
(2) The average duration of the selected category (Table 2).
(3) The maximum duration of the selected category (Table 3).

Figures 1 to 4 inclusive, and Tables 1 to 4, have been selected to show some of the graphic and tabular representations of ceiling information. They have been selected for a small region in central California, extending from the sea coast to the Sacramento Valley. They show considerable variation from one section to another and marked seasonal variations, and illustrate the practical uses which may be made of ceiling information. Figure 5 is a view of one of the cloud phenomena under investigation.

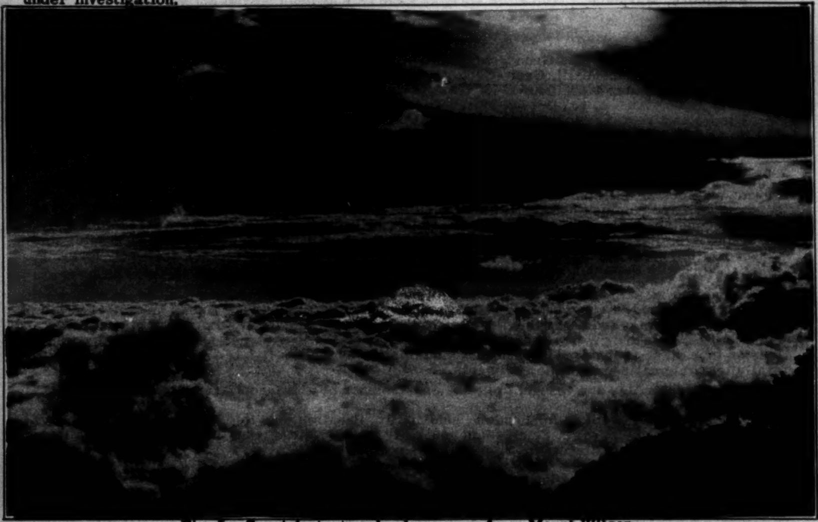

Fig. 5--Coastal stratus clouds as seen from Mount Wilson

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

F. C. PHILLIPS: The micro-fabric of the Moine schists, Geol. Mag., v. 82, pp. 205-220, 1945.

The original investigation (1937) has been greatly extended and the present paper is a summary of the results. A detailed report is to follow later.

The problem is similar to that treated by Kvale and Strand in Norway. An intense lineation trends across the general strike and fabric-diagrams show girdles whose axes are in the lineation direction. The schist is interpreted as a B-tectonite. The Torridonian sandstone, however, does not show this girdle-arrangement and the author thinks that the difference in fabric between the Cambrian and the Moine schist may be due to an older deformation contained only in the latter.

The author tries to prove this by observation in a contact metamorphic zone around the Carn Chuinneag-Inchbae intrusion. The disorderly arrangement of quartz-grains in the hornfels is thought to be the preserved original orientation. Later deformation has superimposed a fabric which is well seen in lineation and girdle-diagrams.

The fabric is thought to have been in existence before the isoclinal folding was impressed upon the schist. Observation on orientation of lineation in relation to fold-axes shows divergence and irregularity which is ascribed to folding of an early lineation.

Furthermore, the author tries to show that the Moine schist-fabric becomes obliterated when the schists become involved in dislocation-metamorphism, particularly in approaching the thrust-area.

The author has measured over 24,000 quartz- and almost 20,000 mica-orientations.

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ANNA HIETANEN: Über das Grundgebirge des Kalantigebietes im südwestlichen Finnland, Ann. Acad. Scien., A, III, Geol.-Geog., Helsinki, 105 pp., 55 text figures, 9 plates; 1 large colored map 1:100,000, 1943.

The Kalanti region is located approximately 200 km west northwest of Helsinki, just south of 61° North Latitude and 21-1/2° East Longitude. It is a portion of the Scandinavian crystalline basement-complex.

The area consists of two groups of rocks: (1) A gneiss-complex of garnet-cordierite rocks, biotite-plagioclase-sillimanite schists, and of amphibolite-lenses of probably volcanic origin. Sandy layers are common but quartzites, conglomerates, and carbonate-rocks are absent. (2) Intrusives consist of a largely concordant trondhjemite complex composed of hornblendites, gabbros, diorites, diorite-trondhjemites, trondhjemites, and trondhjemite-pegmatities. A later and discordant intrusive series consists of granite stocks, dikes, and related veins, locally forming migmatitites with the older sediments. Still later are diabase dikes and rapakivi plutons.

A detailed structural study combined with fabric-analysis (30 orientation-diagrams) shows well-preserved and intensely folded bedding, flow-cleavage, and intense lineation. Intersection of bedding and cleavage indicates the direction of the tectonic axis. Mica-diagrams in sediments and early intrusives show girdles and maxima which are related to s-planes and the tectonic axis. Intrusion took place probably during folding. Migmatite-formation is later. Trondhjemites are generally less migmatized than the sediments.

The trondhjemites are thought to be the end-member of a differentiation-series.

The map shows symbols for bedding, schistosity, lineation, and fold-axes. Folds generally trend E-W or 5° to 40° east. Small folds generally parallel large ones, but at some places two mutually perpendicular directions have been observed.

The trondhjemite shows flow structures, inclusions, schlieren and fractures. The arrangement is conformable to equivalent wall-rock structures.

It may be worth noting that this work was done and the paper published in excellent form in spite of war, bombing raids, and lack of almost all normal facilities.

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DIURNAL VARIATION OF PRECIPITATION AND FORECASTING

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Abstract--The diurnal variation of predisposition for precipitation strengthens and weakens frontal effects periodically and gives rise to a diurnal variation of precipitation. The predisposition is an effect of stability conditions in the atmosphere. Blue Hill Meteorological Observatory, near Boston, Massachusetts, is taken as a station characteristic of the coast, and Jasper, New York, 332 miles west of Blue Hill, is taken to represent inland conditions. Hourly frequencies of rainfall are taken from four years of record. The discussion singles out frequencies of slight (<0.05 in/hour) and heavy ($\geqq 0.10$ in/hour) rainfall intensities. In winter a whole-day wave predominates for both heavy and slight rainfall intensity, but heavy rainfall, inland, shows a rather well developed semidiurnal wave superposed. In summer, semidiurnal waves predominate both at the inland and the coast stations for the two intensities of rain. Numerical tables and diagrams facilitate understanding and provide rapid reference. Apparently instability showers prevail at the coast station, and cyclonic precipitation prevails at the inland station. In summer, at the coast station, a morning maximum of both heavy and slight precipitation-intensity frequency exists, caused by instability showers while an afternoon or evening maximum is of convectional nature (semidiurnal wave). Probabilities are important to the forecaster. For example, the average probability of a heavy snowfall at the coast station during night is 4.3 times as great as in daytime.

Introduction--The principal purpose of this study is to suggest a discussion on the use of certain climatological data for the forecaster rather than to give a few statistical tables.

The diurnal variation of hourly precipitation frequencies may be taken as an example. On the normal physical development of the weather (derived from the field of pressure, temperature, etc.) is superimposed a periodical variation. Thus, at the same time the rainfall is dependent upon an advancing front and is scheduled by its daily course.

Over the sea and the coastal strips, temperature gradients and relative humidity reach their highest values during summer nights, so that the best conditions prevail for moist labile shower activity [see 1 of "References" at end of paper]. During the daytime the land is much warmer than the water, and the dew point of the air-masses originating over the sea surface is depressed. The latter part of this explanation is given by JULIUS HAHN, and is doubted by REFSDAL because "the temperature difference between land and sea cannot immediately influence the formation of precipitation in the higher layers of the atmosphere" and for other reasons. These objections are important, but REFSDAL overlooks, perhaps, that HANN refers rather to the scarcity of rainfall during daytime than to the night maximum. That also is more or less the standpoint of HUMPHREYS [2], although he considers stability conditions too, especially for continental regions with prevailing rainfall during the night. In winter the temperature gradient above the ocean and the coastal regions also may be greater during the night while the relative humidity is certainly higher in the night hours.

This short excursion demonstrates only that a diurnal variation of preparedness of the atmosphere for precipitation can be assumed for physical reasons. At the time of greatest preparedness "weak, old, upper fronts" can more easily release showers than at the time of the minimum of preparedness. In other words, the daily course of preparedness for precipitation may both strengthen and weaken the frontal effects periodically and give rise to a diurnal variation of precipitation.

Studies and results--A practical example for the phenomenon in question is given here in spite of KINCER'S [3] excellent investigation of this problem as it relates to the United States. KINCER laid more stress on the amounts of rain and on the general differences between day and night because of the economic outlook of his study. In this paper frequencies are considered in the form of rainfall probabilities. A discrimination is made, however, between frequencies of

Table 1--Two-hourly diurnal variation of probabilities of precipitation in per cent for Blue Hill Meteorological Observatory, Massachusetts, and Jasper, New York

Hour	All intensities					
	Year		Winter		Summer	
	Blue Hill	Jasper	Blue Hill	Jasper	Blue Hill	Jasper
0- 2	17.9	16.4	16.0	19.5	13.6	9.5
2- 4	17.8	16.3	19.3	18.9	12.5	9.3
4- 6	18.1	17.0	20.0	19.8	12.3	9.5
6- 8	17.7	18.6	19.8	21.3	11.6	9.5
8-10	17.3	20.1	18.7	24.9	10.8	9.4
10-12	15.8	20.4	16.8	27.9	9.9	9.4
12-14	14.6	18.6	15.4	25.2	10.0	10.5
14-16	14.1	16.9	14.9	23.0	10.7	11.2
16-18	14.3	16.3	14.6	21.5	12.5	11.2
18-20	14.9	16.9	14.7	22.3	13.4	11.1
20-22	15.9	17.1	16.3	21.3	13.4	10.7
22-24	16.9	16.8	17.7	19.0	12.9	10.5
Max/min	1.28	1.25	1.37	1.48	1.37	1.20
Average	16.3	17.6	17.3	22.1	11.9	10.2
	<0.05 in/hr					
0- 2	10.7	12.1	10.9	15.8	7.4	5.8
2- 4	10.9	12.2	11.1	15.0	7.3	6.1
4- 6	11.7	13.0	12.1	16.2	7.6	6.9
6- 8	11.7	14.4	12.9	17.7	7.5	7.1
8-10	11.4	16.1	13.3	21.6	6.7	6.9
10-12	10.3	16.5	12.3	24.5	5.8	6.2
12-14	9.6	14.9	10.3	22.5	6.0	6.7
14-16	9.2	13.2	9.1	20.6	6.9	7.3
16-18	8.9	12.4	8.0	19.7	8.3	7.3
18-20	9.1	12.6	7.8	20.0	8.4	7.3
20-22	9.4	12.5	8.4	18.9	8.5	6.6
22-24	10.5	12.0	9.5	15.5	7.6	6.4
Max/min	1.20	1.38	1.71	1.63	1.47	1.26
Average	10.2	13.5	10.5	19.0	7.3	6.7
	≥0.10 in/hr					
0- 2	3.6	1.8	4.7	1.0	2.5	2.1
2- 4	3.3	1.8	3.9	1.2	2.6	1.5
4- 6	2.8	1.4	2.9	1.2	2.6	1.5
6- 8	2.4	1.4	1.8	1.0	2.5	1.2
8-10	2.0	1.4	1.3	0.8	2.1	1.4
10-12	2.1	1.5	1.1	0.7	1.9	1.5
12-14	2.1	1.6	1.6	0.7	2.0	2.2
14-16	2.3	1.7	2.2	0.6	2.3	2.2
16-18	2.5	1.7	2.9	0.3	2.7	2.2
18-20	2.7	1.8	3.4	0.5	2.8	2.1
20-22	3.2	2.1	4.2	0.6	2.9	2.4
22-24	3.4	2.1	4.7	1.0	2.6	2.3
Max/min	1.80	1.50	4.27	4.00	1.53	2.00
Average	2.7	1.6	2.9	0.8	2.5	1.9

Note: The original frequency numbers for the total of the years 1940 to 1943 can be recalculated from the probabilities by multiplying by 1461, 361, and 368, respectively, for the year, winter and summer.

slight (<0.05 in/hour) and heavy rainfall ($\geqq 0.10$ in/hour) because of possibly different causes. A new publication [4] permitted this more detailed representation as well as the consideration of the full year in contradistinction to former investigations [2, 3].

Because of the different physical conditions in winter and summer, average probabilities are given for the two seasons, and statistics for the whole year are added for sake of completeness.

Two places are chosen from the publication [4] which covers only the North Atlantic district of the United States. The first is the Blue Hill Meteorological Observatory (42°13′ N, 71° 07′W) representing the coastal climate, and the second, Jasper, New York (42°09′N, 77°35′ W), the best available continental station. It is located 332 miles inland from Blue Hill, and lies west of the Alleghenies. It is more than 60 miles from the shores of Lake Erie, so that a possible influence of the Great Lakes on the daily course of rainfall may be excluded.

The records of Blue Hill are complete. CHARLES F. BROOKS kindly supplied handwritten data for February 1940 and June 1943. The records of Jasper show some gaps which were interpolated cautiously from the records of two stations close by, Thurston, New York (42°12′N, 77°20′W), and Burns, New York (42°25′N, 77°44′W).

Unfortunately only four years' records are available, a very short period in comparison with the great variability of the values in question, especially as far as the inland station is concerned.

Jasper, New York, had 19 hours with rainfall $\geqq 0.10$ inch per hour in 1940 and only one hour in 1943. The respective numbers from Blue Hill were 135 and 94. The variability is much smaller, but incidentally the years of extremes agree with one another at the two places. As a consequence of these conditions only two-hourly values are given in Table 1 which have been smoothed by the formula $(a+b+c)/3$. Smoothing appears justified in consideration of the much smoother curves that naturally would result from longer periods. Figure 1 shows the same data for the light and heavy intensities of rainfall.

Conclusions--Some conclusions can be drawn from the data presented:

(1) A climatic difference between coast and inland can be derived from the average rainfall probabilities("average" lines of Table 1). In winter slight rainfall is nearly twice as probable inland as on the coast, and heavy precipitation is almost four times as probable on the coast as in the interior. In summer these features are not well developed. Slight rains in the interior are more frequent only from 8^h through 16^h, and the average frequency is even somewhat smaller than that on the coast. In summer, heavy rains are more frequent in the interior only between noon and 14^h; on the average (bottom line) the probability of heavy rain is 30 per cent greater on the coast. If the entire year is considered, the averages show 32 per cent greater probability of slight rains inland and 69 per cent greater probability of heavy rains on the coast. From these relationships, the inference can be drawn that instability showers[5], according to the classification of BJERKNES and SOLBERG, prevail near the coast, and cyclonic rains prevail inland. In the paper mentioned, the fact is emphasized that instability showers "are experienced in all seasons, but most frequently and typically in winter." Thus, the meteorological experience is in agreement with the statistical results of this investigation.

(2) As indicated by Figure 1, the majority of the diurnal variations are not very simply shaped, even when smoothed, perhaps because of the limited period available. (The attempt was made to analyze each three courses of Blue Hill and Jasper by means of FOURIER'S series. Remarkably, all three Blue Hill series converge quite well, so that at least in two cases waves with lengths of a fraction of a day could be neglected at first approximation. Jasper, the inland station, yields non-convergent series, the meaning of which can hardly be interpreted. It is not impossible that such a behavior could be characteristic of increasing continentality.)

For an easier survey, Table 2 gives the hours of the extremes separately for winter and summer, for both the coast station and inland station, and for heavy and slight intensities of rainfall.

Table 2--Time of extremes of probability of heavy and slight rainfall intensity at Blue Hill Observatory, Massachusetts, and Jasper, New York

	Winter				Summer			
	Blue Hill		Jasper		Blue Hill		Jasper	
	Max	Min	Max	Min	Max	Min	Max	Min
Heavy	0^h	11^h	4^h	17^h	$5^h;21^h$	$1^h;11^h$	$15^h;21^h$	$7^h;19^h$
Slight	9^h	19^h	11^h	3^h	$5^h;21^h$	$3^h;11^h$	$7^h;19^h$	$1^h;11^h$

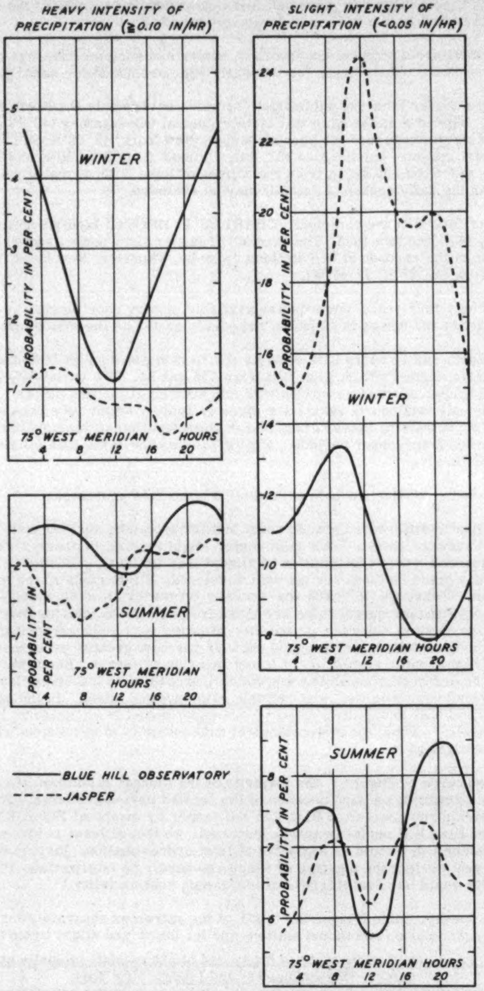

Fig. 1--Diurnal variation of probabilities of heavy and slight precipitation at Blue Hill Observatory, Massachusetts (on the coast), and Jasper, New York (inland)

Discussion--The diurnal variations may be described as follows:

In winter, on the average, the frequency extremes of slight precipitation intensity follow those of heavy intensities by eight to nine hours. At the coast station, the maximum frequency of heavy intensity occurs at midnight, the minimum at about noon. This socalled "oceanic type" is, however, not observed in the case of slight intensity with maximum in the forenoon and minimum in the evening hours. At the continental station (Jasper) the heavy intensity also shows the "oceanic type" (maximum in the night, minimum in the afternoon). Slight precipitation intensity, however, is characterized by a night minimum and an accentuated maximum about noon; the physical explanation offers difficulties. Even if the amplitude is nearly negligible, the daily course is obviously real.

In summer, the character of the diurnal variation at the coast station, as well as the inland one, is entirely changed. In winter, the daily course can be represented as a whole day wave. In summer, the semidiurnal variation plays an important role, as may be seen in the tables, and more clearly in Figure 1.

At Blue Hill, slight and heavy intensity of precipitation have more or less identical courses; one maximum occurs in the morning hours, the other in the evening hours. The results derived from the Blue Hill records are clear. The morning maximum can be taken as caused by conditions of instability; the evening maximum, by convectional rains. At the inland station, the greater maximum of heavy rain frequency occurs in the night and the convectional afternoon maximum is of secondary nature. The strong minimum in the morning hours corresponds to what is expected.

The discrimination between slight and heavy rainfall apparently shows that the usual explanation of the diurnal variation of precipitation is not fully satisfactory. Further investigation into the interesting details of the daily courses should embody at least ten years' incontestable records of suitably located places.

Insofar as it can be deduced from KINCER'S night-rain maps [3], the complicated conditions which cause the diurnal variation of precipitation can be disentangled only by a regional investigation considering the regional conditions of the atmosphere. Thus, conversely, a certain diurnal variation could give some information about average conditions of stability in the atmosphere above the region in question.

Finally a short remark may be made about the probabilities given in Table 1. They are obviously very characteristic from the climatological standpoint, but they are not so important from the viewpoint of the forecaster who deals with the actual, momentary probability. The average probability of a heavy snowfall is three per cent, the actual of the respective day may be 80 per cent. Granted that, the preparedness of precipitation offers a new point of view. For this reason the lines "maximum/minimum" were added in Table 1. These numbers mean the ratios of the extreme probabilities of the different diurnal variations. The highest ratios appear with heavy intensity of precipitation in winter. In this season the probability of heavy snowfall at the coast station is 4.3 times greater in the two hours before and after midnight (with equal probabilities of 4.7 per cent, see Table 1) than during the hours 10 a.m. to noon. Similar relations exist at the inland station. Also, in summer the ratio of probabilities of heavy intensity of rain during late evening hours and during the forenoon is 1.53 and 2.00, respectively. Other interesting features can easily be taken from Table 1.

As it was stated previously, the local weather effect of a passing front is to a certain degree dependent upon the time of its arrival according to the diurnal variation of rainfall preparedness (probabilities). This may be worth noting by the forecaster.

Acknowledgement--I am indebted to Dr. and Mrs. HANS NEUBERGER, State College, Pennsylvania, for their linguistic comments.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

F. A. VENING MEINESZ: Nieuwe formules voor schietloodafwijkingssystemen en het theorema van Laplace, Vers. Ned. Akad. Wet., v. 53, no. 4, 1944.

We can simply prove that the theorem of Laplace for the relation between the deviations in longitude and in azimuth is exact up to terms of the order of the second power of the deviations of the vertical. This leads to doubts regarding Helmert's formulas for systems of deviations of the vertical which add terms to this theorem proportional to the first power of the components ξ_0 and η_0 of the deviation of the vertical in the central station P_0 of the system. This appears to be caused by the method of Helmert who, in introducing ξ_0 and η_0 in P_0, shifts the geodetic line P_0P_1 while keeping its azimuth in P_0 and its length the same, instead of projecting P_0 P_1 on the ellipsoid after its being shifted in such a way that the components ξ_0 and η_0 originate in P_0. The study of this problem has led to the formulas for the changes in the components ξ_1 and η_1 of the deviation of the vertical in P_1 caused by the introduction of ξ_0 and η_0 in P_0. If P_1 has a height h above sea-level these formulas have to be replaced. For systems of limited extension in the sense of the parallel we may use the simplified formulas.

The differences are represented by the two equations:

$$\delta\Delta\xi_1 = [\cos(\lambda_1-\lambda_0)-\cos(\phi_1-\phi_0)+2\sin\phi_1\sin\phi_0\sin^2 1/2(\lambda_1-\lambda_0)]\,\xi_0 - \\ -(\sin\phi_1-\sin\phi_0)\sin(\lambda_1-\lambda_0)\eta_0$$

$$\delta\Delta\eta_1 = -(\sin\phi_1-\sin\phi_0)\sin(\lambda_1-\lambda_0)\xi_0 + \\ +[\cos\phi_1\sec\phi_0-\cos(\lambda_1-\lambda_0)+\cos\phi_1\operatorname{tg}\phi_0\operatorname{csc}a_{01}\cos a_{10}\sin(\lambda_1-\lambda_0)]\,\eta_0.$$

It follows from our investigation that we can apply the theorem of Laplace independent of the value of ξ_0 and η_0 in P_0. It results also that for each change of ξ_0 and η_0 the triangulation network slightly changes its shape. It further appears desirable to introduce a third component, ΔN_0 of the shift of the ellipsoid in the direction of the vertical of the central station P_0.

AUTHOR

F. A. VENING MEINESZ: Gravity over the Hawaiian Archipelago and over the Madeira area; conclusions about the Earth's crust, Proc. Ned. Akad. Wet., v. 44, no. 1, 1941.

The author points out that both the Hawaiian Archipelago and the Madeira area of volcanic origin are situated in deep-sea regions. He assumes that each group of islands has an average density of 10 to 15 per cent greater than the surrounding rock, extending from the level surface of the surrounding deep-sea ocean-bottom to the surface of the islands. These heavy island masses are assumed to be regionally compensated, depth of compensation, 30 km.

The author finds for a depth of compensation of 30 km, the average anomaly is a minimum for 3.07 density of island masses when the radius of the region of compensation is 174.3 km, or for 2.937 density when radius is 232.4 km. The average anomalies without regard to sign for the five areas considered are 15 and 11 milligals, respectively, while for local compensation and 30 km depth of compensation the respective average anomalies are 88 and 81.

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Transactions, American Geophysical Union   Volume 27, Number I   February 1946

THE MOISTURE-FACTOR IN CLIMATE

C. W. Thornthwaite

Abstract--It is pointed out that in order to evaluate the moisture-factor in climate, the moisture supply or the precipitation must be compared with the water-needs or the potential evapotranspiration. The distribution of precipitation through the year never coincides with, and seldom parallels, the distribution of potential evapotranspiration. When the precipitation is in excess of the need, the surplus goes to recharge ground-water and produce runoff. When the precipitation does not equal the need, there is a deficiency which results in drought. Data on precipitation and potential evapotranspiration are presented for sixteen stations in the United States and tropical America.

Climatology has been defined as statistical meteorology, and is said to deal with the regularly recurrent or periodic changes in the physical state of the atmosphere, from day to night and from summer to winter. The principal elements of climate that are observed are temperature, pressure, humidity, wind, solar radiation, and precipitation. The first four of these elements are qualities of the atmosphere, but the last two relate rather to the Earth's surface, one constituting the source of soil-temperature and the other the source of soil-moisture. Nevertheless, radiation and precipitation are climatic factors of major importance, because climate has to do with more than the state of the atmosphere. Climate deals, in addition, with the conditions of temperature and moisture of the soil and with the interactions between soil-surface and atmosphere. Soil-temperature and soil-moisture are climatic elements. Climatology is more than statistical meteorology.

That precipitation in itself is inadequate as a climatic factor is no novel idea. The fact was recognized in the United States Weather Bureau more than 50 years ago. In 1894, only three years after it had been established in the Department of Agriculture, a Division of Agricultural Soils was created. MILTON WHITNEY, first Chief of this Division, explained the interest of the climatologist in the soil in these words [see 1 of "References" at end of paper, p. 1]:

> "Rain is of little benefit to plants until it enters the soil where it can be absorbed by their roots. It is extremely important, therefore, to continue the study of the rainfall further than has heretofore been done, and to keep a record of the amount and distribution of the moisture and temperature within the soils adapted to different agricultural crops."

The stated objective of the Division was [1, p. 1] to continue "the study of rainfall and temperature after they enter the soil, and to keep a continuous record of the moisture and temperature conditions within some of the most important types of soil in the country."

Unfortunately for climatology, within two years the Division of Agricultural Soils was separated from the Weather Bureau and became an independent unit in the Department of Agriculture. After it grew into the Bureau of Soils a few years later, the original climatic orientation of its work was largely forgotten. The Weather Bureau did not, however, resume the study of the moisture-factor of climate, but limited its task largely to the collection of records of precipitation.

In 1900, the distinguished climatologist, W. KÖPPEN, voiced the need for investigating soil-moisture in determining the moisture-factor of climate. He said [2, pp. 603-604]:

> "Presumably a time will come when we shall be able to determine the local and geographic differences in the amount of water available to the soil for nourishing plants, just as we now determine amounts of rainfall and air temperature, and maps will be made of this important factor that will be comparable with the maps of evaporation values. We may expect that the clarification of these important questions will be one of the first tasks of the current, much discussed, 'agricultural meteorology.' "

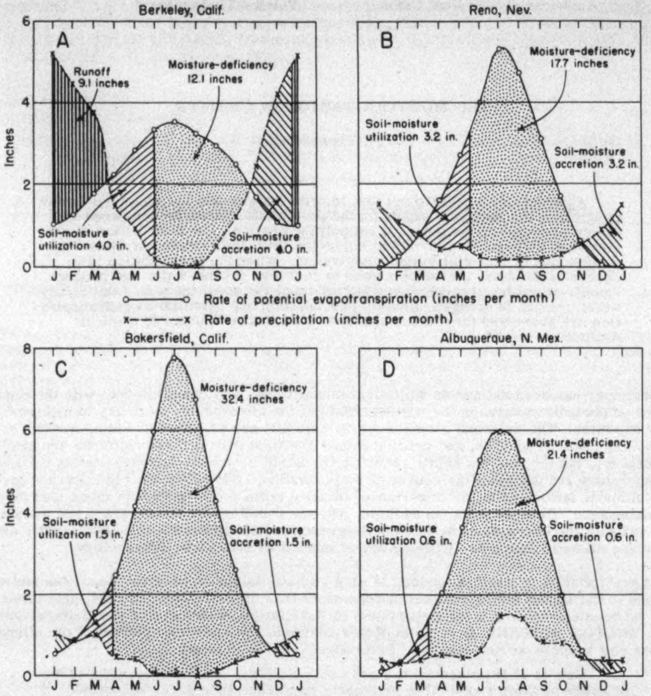

Fig. 1--March of potential evapotranspiration through year at representative stations, Berkeley (California), Reno (Nevada), Bakersfield (California), and Albuquerque (New Mexico)

There is no doubt that records of the moisture-conditions of the soil are a valuable addition to records of precipitation in evaluating the moisture-factor of climate. They do not provide a complete evaluation, however. To make such an evaluation the amount of water that would be transferred from the soil to the atmosphere by evaporation and transpiration, if it were constantly available in optimum quantity, must be compared with the moisture that is actually transferred. The first may be called the potential evapotranspiration, the other the actual evapotranspiration.

The many observations of loss of water to the atmosphere from land areas, made in irrigation projects, on experimental plots, lysimeters, and small watersheds, show that potential evapotranspiration is dependent primarily on the intake of solar radiation by plants and the soil-surface and on the temperature of the adjacent layer of air, and that actual evapotranspiration is limited by the supply of available soil-moisture and is usually less than that potentially possible. These observations are confirmed by studies of the moisture requirements of plants in various parts of the country. On the basis of these observations, we were able to develop an empirical formula by means of which both potential and actual evapotranspiration can be determined from ordinary Weather Bureau records of temperature and precipitation. This formula, together with a map showing the distribution of average annual evapotranspiration, has already been presented in a previous report [3].

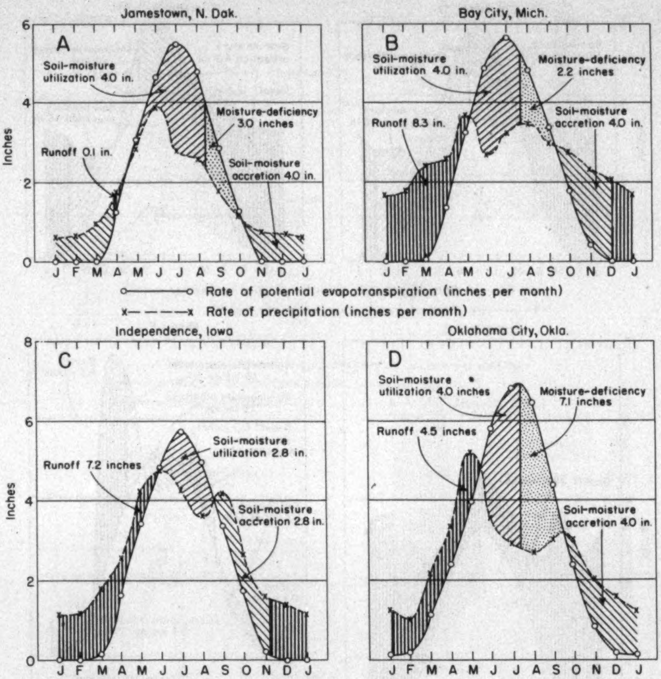

Fig. 2--March of potential evapotranspiration through year at representative stations, Jamestown (North Dakota), Bay City (Michigan), Independence (Iowa), and Oklahoma City (Oklahoma)

In this paper, I present a series of curves showing the march of potential evapotranspiration and precipitation through the year at a number of selected representative stations. Twelve stations are in various parts of the United States and the other four are in tropical America. They are given in Figures 1 to 4. Annual totals of potential evapotranspiration, precipitation, actual evapotranspiration, runoff, and moisture-deficiency for these stations are given in Table 1.

Since the amount of water that plants can lose to the atmosphere increases with temperature and the amount of sunshine, the needs are greatest in summer and in hot climates. In the northern United States annual potential evapotranspiration is less than 20 inches, whereas in southern Florida and south Texas it is more than 50 inches, and in parts of southern California more than 60 inches.

Except in equatorial climates, the potential evapotranspiration varies systematically from month to month through the year; it is quite small or negligible in the winter and, outside the polar regions, is large in the summer. In tropical America the periodic variation between winter and summer values of potential evapotranspiration, associated with astronomic variation in the incidence of solar radiation, gradually diminishes until it disappears at the equator (see Fig. 4B). Potential evapotranspiration may vary from month to month, however, even in full equatorial climates. Where

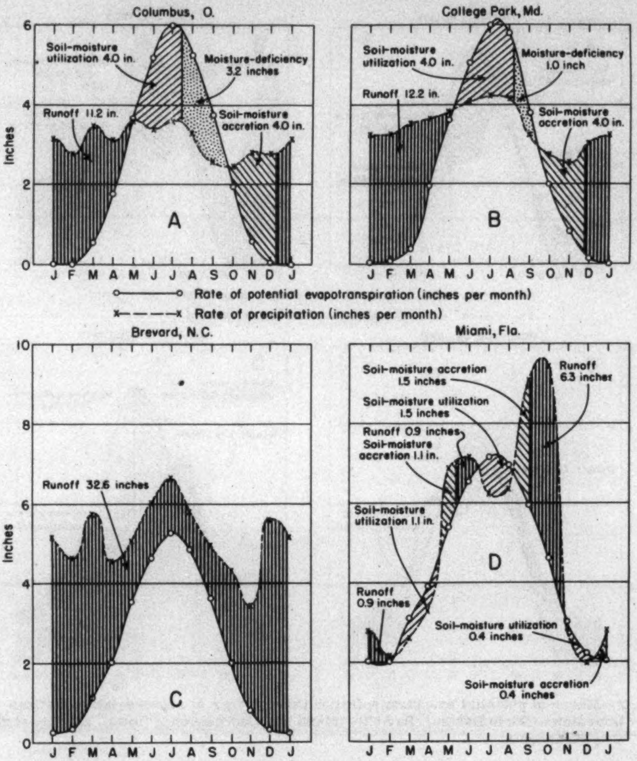

Fig. 3--March of potential evapotranspiration through year at representative stations, Columbus (Ohio), College Park (Maryland), Brevard (North Carolina), and Miami (Florida)

there is a strong periodicity of precipitation, variation in cloudiness will impose a corresponding variation on solar radiation and thus on potential evapotranspiration. For example, in Manaos, Brazil (Fig. 4D), within 3° of the equator, maximum values of potential evapotranspiration are in August, September, and October, during the dry season, and minima are in February at the height of the rainy season. In Tacubaya, Mexico, the maximum comes in May near the end of the dry season (Fig. 4A).

The march of potential evapotranspiration through the year follows a uniform pattern in most of the United States. In the winter months it is negligibly small as far south as the Gulf Coastal Plain; it is only about two inches per month in southern Florida (Fig. 3D). In July it rises to a maximum that ranges from five inches along the Canadian Border to seven inches on the Gulf Coast. In some mountain areas and along the Pacific Coast, the July potential evapotranspiration is less than five inches; in Berkeley, California (Fig. 1A), it is less than four inches. In a part of south Texas the summer maximum is more than eight inches and in some of the desert areas of Arizona

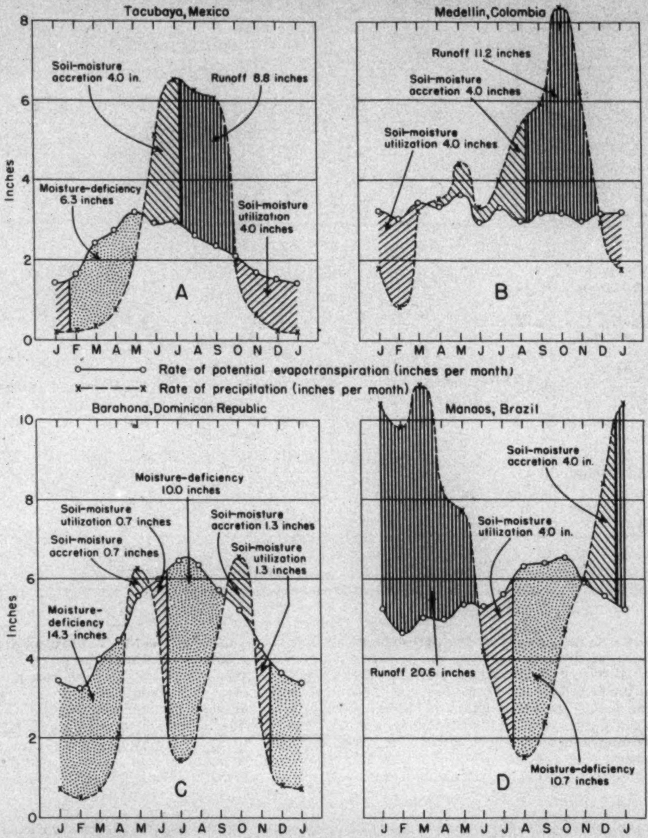

Fig. 4--March of potential evapotranspiration through year at representative stations, Tacubaya (Mexico), Medellin (Colombia), Barahona (Dominican Republic), and Manaos (Brazil)

and southern California it is in excess of ten inches.

The march of precipitation through the year is highly variable from one region to another. In tropical America there are large seasonal variations of rainfall, with pronounced rainy and dry seasons. The rainy period usually occurs at the time of the Northern Hemisphere summer (Fig. 4A). There are some regions in the tropics, however, that have double maxima and minima, with dry seasons occurring in both winter and summer, and rainy seasons in spring and autumn (Fig. 4C). In most of the United States there is a tendency, more or less developed, for a maximum amount of precipitation to fall during the growing-season. In the Pacific Coast states the distribution is reversed, with the maximum in winter and very little during the summer (Figs. 1A, 1B, IC).

Table 1--Comparative moisture-data of selected stations, in inches

Station	Potential evapo-transpiration	Precipitation	Actual evapo-transpiration	Runoff	Moisture-deficiency
Berkeley, California	27.28	24.25	15.20	9.06	12.08
Bakersfield, California	37.95	5.55	5.55	0.00	32.40
Reno, Nevada	24.84	7.13	7.13	0.00	17.71
Albuquerque, New Mexico	29.57	8.03	8.03	0.00	21.54
Jamestown, North Dakota	22.84	19.92	19.84	0.08	3.00
Independence, Iowa	25.71	32.95	25.71	7.24	0.00
Oklahoma City, Oklahoma	34.21	31.54	27.09	4.45	7.12
Bay City, Michigan	24.92	30.98	22.68	8.31	2.24
Columbus, Ohio	28.11	36.18	24.96	11.22	3.15
College Park, Maryland	29.45	40.75	28.54	12.21	0.91
Brevard, North Carolina	28.50	61.06	28.50	32.56	0.00
Miami, Florida	52.24	59.84	52.24	7.60	0.00
Tacubaya, Mexico	27.64	30.12	21.30	8.82	6.34
Medellin, Colombia	38.11	49.21	37.99	11.22	0.12
Barahona, Dominican Rep.	57.60	33.31	33.31	0.00	24.29
Manaos, Brazil	66.06	75.94	55.39	20.55	10.67

In the states bordering on the Ohio River and those to the south immediately east of the Mississippi, the distribution of precipitation is quite uniform throughout the year except for a slight autumn minimum.

Since the meteorologic forces that determine the amount and distribution of precipitation are not the same as those that govern the need for it, there is no causal relation between precipitation and potential evapotranspiration. Presumably, an ideal climate is one in which the march of precipitation through the year coincides with the march of potential evapotranspiration. But in most parts of the world, the distribution of rainfall through the year does not coincide with the changing demands for water. Where the rainfall is uniform from season to season, or where there is a maximum in winter, there may be a surplus in winter that runs off and a deficiency in summer when the need is great; that results in drought. On the other hand, in regions of pronounced summer rainfall, a surplus may occur at that season, with ensuing runoff, and a deficiency may be experienced in winter.

In some parts of the Earth more rain falls month after month than the vegetation can use. The surplus moves through the ground and over it to form streams and rivers, and flows back to the sea. In some other regions, month-after-month rains provide less water than the vegetation could use if it were available. There is no excess of rainfall and thus there are no permanent rivers and no drainage to the ocean. We cannot tell whether a place has a rainy or dry climate merely by knowing the rainfall. We must know whether the rainfall is more or less than the needs for evaporation and transpiration. In south Texas, where the potential evapotranspiration is 50 inches, the climate would be dry at least for a part of the year with any smaller amount of rainfall. In northern Canada, on the other hand, ten inches of precipitation is ample for all plant-requirements and is enough to make a rainy climate. Long ago, KÖPPEN [2, p. 605] observed that in southern Russia the roads were dry and dusty during the rainy summer and muddy during the less rainy winter.

Drought does not begin immediately after the rate of precipitation falls below the rate of potential evapotranspiration. Moisture accumulates in the soil at times of excess rainfall, and that which is within reach of roots is utilized before the plants begin to suffer from moisture-deficiency.

The amount of water that may be stored in the root-zone varies with the soil-structure and the distribution of the roots, but is in the order of 4.0 inches [4].

There are very few areas where moisture is not deficient at some time during the year. Of the 16 stations summarized in Table 1, only three have no moisture-deficiency. Of these three, Brevard, North Carolina (Fig. 3C), has a surplus of rainfall in every month; the total precipitation is more than twice as much as the evapotranspiration and the runoff is 32.6 inches. In some places the precipitation is very much less than the need (for example, Bakersfield, Reno, and Albuquerque, on Fig. 1) and runoff does not occur. Even when the total precipitation is deficient, it is sometimes so badly distributed through the year that considerable runs off. In Berkeley, California (Fig. 1A), the average annual precipitation is 24 inches and the potential evapotranspiration is 27 inches. Despite the failure of the precipitation to meet the need, there is a winter surplus resulting in nine inches of runoff and, consequently, the moisture-deficiency is 12 inches instead of three. Likewise, in Oklahoma City there is more than four inches of runoff although the average annual precipitation fails by three inches to meet the annual evapotranspiration need.

The fact that annual precipitation is in excess of the need for water does not preclude a possible period of moisture-deficiency. In Manaos, Brazil, the average annual rainfall is 76 inches and the potential evapotranspiration only 66 inches. However, the runoff is 21 inches instead of ten,and there is a moisture-deficiency of 11 inches, extending over a period of nearly four months.

When the changing rate of potential evapotranspiration through the seasons is known,it can be compared with the precipitation, and the time and amount of surplus and deficiency of moisture determined. Farming operations can be examined with respect to the period of probable drought and cropping-schedules adjusted or the moisture-deficiency eliminated through the use of supplementary irrigation. Studies on the relation of moisture-supply to crops can be greatly improved. Instead of relating yields to deviation from the normal rainfall of successive periods, it will be possible to consider instead the deviations of the rainfall from the amounts needed in the successive periods. There are many regions where measurements of runoff have not been made. The surplus of moisture that will appear as runoff and the time when it becomes available can be determined from data on temperature and precipitation. Thus, in any region where climatological records are available, mean runoff can be computed.

Knowledge concerning the rate of transfer of moisture from the land-surface to the atmosphere should also be of value in forecasting precipitation, especially during the summer months. Although the July evapotranspiration in eastern United States ranges from five inches along the Canadian Border to seven inches on the Gulf Coast, in most of the area east of the 100th meridian the average loss to the atmosphere is between 5.5 inches and 6.5 inches. According to data derived from SVERDRUP [5, p. 233], the evaporation during July from the water surface in the Gulf of Mexico and the Carribean is only about 4.0 inches. Thus the moisture contributed to the atmosphere by the land-area of eastern United States is greater than that from the sea.

The average daily evapotranspiration during July in eastern United States is approximately 0.2 inch and,during periods of hot weather when there is abundant moisture in the soil, the rate even in the northern part of the country, may exceed 0.3 inch for several consecutive days. The actual amount of water evaporated into the air on a midsummer day in eastern United States depends far more on the amount of available moisture in the soil than it does on the condition of the atmosphere. Plants can obtain little water from a dry soil and little is contributed to the atmosphere. Thus the daily evapotranspiration may vary from almost nothing to 0.3 inch or more. HOLZMAN [6] computed the total average depth of water in the atmosphere over the United States for July, 1936. In the east it ranged from less than 0.9 inch at the Canadian Border to more than 1.7 inches on the Gulf Coast. From this it is evident that the daily increment of moisture to the atmosphere through evapotranspiration may be a considerable fraction of the total. It averages one-sixth to one-eighth and at times it may be as much as one-third to one-fourth. As much as two-thirds of the daily evapotranspiration occurs during five mid-day hours.

When the maximum amount of water is transferred to the atmosphere, the air-masses, from whatever source, are greatly modified, regardless of whether they are in continuous motion or remain stationary for considerable periods of time. Thus, to improve the forecasting of air-mass thunderstorms, if of no others, the moisture-condition of the soil and the evaporation from it should be taken into account.

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[6] BENJAMIN HOLZMAN, Sources of moisture for precipitation in the United States, U. S. Dep. Agric. Tech. Bull. No. 589, 1937.

U. S. Soil Conservation Service,
Washington, D. C.

(Manuscript received June 14, 1945; presented at the Twenty-Sixth Annual Meeting, Washington, D. C., May 31, 1945; open for discussion until July 1, 1946.)

NOTES AND PERSONALIA

(See also pp. 14, 59, 60, 68, 107, 110, 118, and 120)

PERSONALIA

Boris A. Bakhmeteff, Professor of Civil Engineering at Columbia University, has been elected to honorary membership in the American Society of Civil Engineers.

Merrill Bernard, Hydrologic Director of the United States Weather Bureau, is the recipient of the Norman Medal of the American Society of Civil Engineers for his paper entitled, "Primary role of meteorology in flood flow estimating."

Joseph C. Boyce, Professor of Physics at Massachusetts Institute of Technology, has resigned to become Chairman of the Department of Physics, New York University.

Eugene Callaghan, formerly geologist with the United States Geological Survey, has been appointed Professor of Economic Geology at Indiana University.

Frederic M. Chace of the Civilian Production Administration has transferred to the United States Geological Survey and is now Gold Commodity Geologist in the Metals Section.

Sidney Chapman, Professor of Mathematics at Imperial College of Science and Technology in London, has accepted an appointment to a professorship at Oxford University.

Luke A. Cole, Mathematician, of the United States Coast and Geodetic Survey, retired on October 31, 1945, after 43 years of service. He was Chief, Section of Datum Planes of the Division of Tides and Currents.

Harold E. Culver was appointed delegate of the American Geophysical Union to the inauguration of Wilson M. Compton as President of Washington State College, December 11, 1945.

Charles F. Deiss has been named Chairman of the Department of Geology at Indiana University, and Director of the State Division of Geology. Formerly, he was a geologist with the Nonmetals Section of the United States Geological Survey.

George T. Faust has been appointed Professor of Mineralogy at Indiana University. Formerly he was mineralogist with the United States Geological Survey.

Charles J. Fish, Commander in the Mine Warfare Section of the Navy Department, has gone to Japan on a special assignment during which he will visit the oceanographic laboratories. This calls to mind a recent item in Science (November 23, 1945, p. 526) in which was noted that a poster found on the doors of the Oceanographic Institute of the University of Tokyo read as follows:

> "This is a marine biological station with her history of over sixty years; If you are from the Eastern Coast, some of you might know Woods Hole or Mt. Desert or Tortugas; If you are from the West Coast, you may know Pacific Grove or Puget Sound Biological Station; This place is a place like one of these; Take care of this place and protect the possibility for the continuation of our peaceful research; You can destroy the weapons and the war instruments; But save the civil equipments for Japanese students; When you are through with your job here, notify to the University and let us come back to our scientific home;
>
> THE LAST ONE TO GO"

Transactions, American Geophysical Union Volume 27, Number I February 1946

AN INDUCTION-MAGNETOMETER--PRINCIPLE OF OPERATION

A. G. McNish

Abstract--A simple form of saturated-core induction-type magnetometer is described and the principle of its operation is briefly discussed. This version of the instrument employs no electronic components. Possibility of its application as a universal instrument for geomagnetic measurements is suggested.

The basic principles of the induction-magnetometer were employed shortly before the war in an endeavor to produce a simple rugged instrument for magnetic measurements in connection with the degaussing of ships. The magnetometer depends for its operation upon the variation of permeability of some highly susceptible material, such as permalloy, with variations in a weak magnetic field. One of the first instruments employing this principle is described by H. ASCHENBRENNER and G. GOUBAU [see 1 of "References" at end of this paper]. Their device employed a vacuum-tube oscillator and a tuned amplifier and was intended for the measurement of small and rapid changes in the Earth's field. The device described in this paper is somewhat simpler in construction and is intended for measurement of the total field-strength.

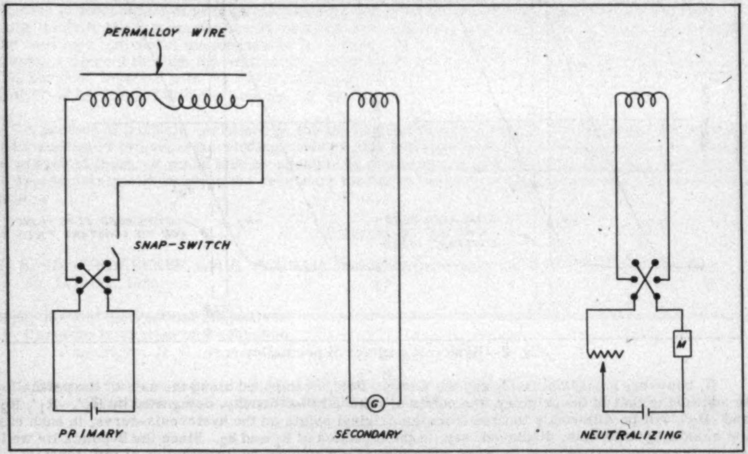

Fig. 1--Galvanometric circuit of induction-magnetometer

The magnetometer consists of three separate simple circuits (see Fig. 1) coupled by means of a long permalloy wire. The primary is a single-layer helix with direction of winding reversed in the middle into which is inserted a thin permalloy-wire core. This primary is connected to a battery through a snap-switch and a reversing-switch, so that the solenoid may be suddenly energized or de-energized. A secondary coil is mounted at the center or point of reversal of the primary and is connected to any simple type of galvanometer, preferably one of fairly large resistance. The primary-and-secondary assembly is mounted inside a solenoid connected through a reversing-switch to a battery, rheostat, and meter. Observations are made by operating the snap-switch and observing any resultant deflection of the galvanometer. The neutralizing-current is adjusted until zero-deflection of the galvanometer is obtained. The reading of the meter in the neutralizing-circuit together with the coil-constant of the solenoid affords a measure of the

strength of the magnetic field along the axis of the permalloy wire.

The principle of operation may be appreciated by considering the hysteresis-loops for the two halves of the permalloy wire. Let S_1, R_1, $-S_1$, and $-R_1$ represent points on the hysteresis-curve corresponding to the saturation and remnant flux-densities, positive and negative, for one-half of the permalloy wire, and S_2, R_2, $-S_2$, and $-R_2$ the corresponding points on the hysteresis-loop for the other half of the permalloy wire (see Fig. 2). When the primary is energized, the one-half of the permalloy wire is saturated to the point S_1, the primary current being adjusted so that saturation is obtained. The other half of the permalloy is saturated at $-S_2$, owing to the reversal of the primary winding at its midpoint. When the snap-switch is opened the first half of the permalloy drops to the point R_1 and the second half of the permalloy drops to the point $-R_2$. Provided the two haves of the permalloy are identical and the two halves of the primary are equal, the change in flux-density and in total flux when the cycle passes from S_1 to R_1 and from $-S_2$ to $-R_2$, will be equal but opposite in sign, so long as there is no field applied to the permalloy wire other than that of the primary. Consequently, no current will be induced in the secondary, provided it is centrally mounted. The primary switch is then reversed and the circuit closed, bringing the two halves of the permalloy to $-S_1$ and to $+S_2$. Again, assuming that the above conditions are satisfied, no current is induced in the secondary.

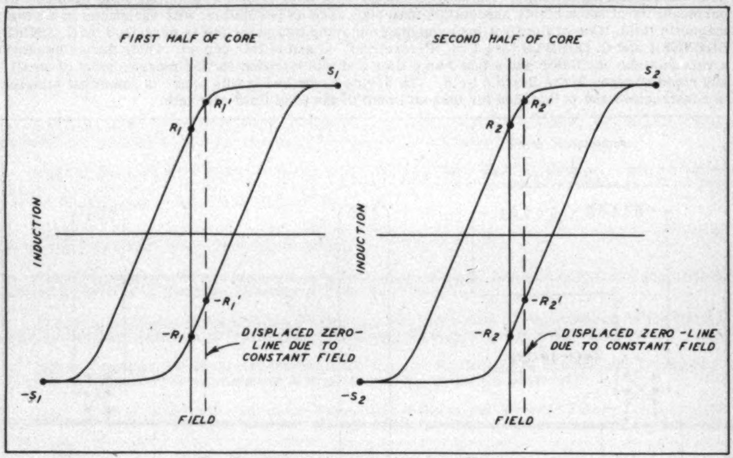

Fig. 2--Hysteresis cycles of permalloy core

If, however, a constant field, say the Earth's field, is imposed along the axis of the permalloy in addition to that of the primary, the points of residual flux-density, designated by R_1', $-R_1'$, R_2', and $-R_2'$, will be differently located from the original points on the hysteresis-curve, in each case the residual points being displaced, say, in the direction of S_1 and S_2. Since the S-points lie well out on the saturation-curves, they are not effectively displaced by introduction of this constant field. Energizing the primary so that both halves of the permalloy are saturated, and then breaking the current, will bring the first half of the permalloy from S_1 to R_1', while the second half will drop from $-S_2$ to $-R_2'$. The flux-changes in the two halves of the permalloy are not equal under these conditions and consequently a deflection of the galvanometer is produced. The sense of the deflection depends upon how the constant field was applied with respect to the previously assumed positive direction. This additional field must be compensated by the neutralizing-solenoid in order that the galvanometer show no deflection when the snap-switch is manipulated.

In order that the device should be sensitive to small fields, the effective permeability of the core-material must be great. End-effects shear the hysteresis-curve, reducing the effective permeability, so that the dimension-ratio of the core must be large. In most experimental models, a dimension-ratio of over 300 has been used. Increasing the length of the core increases the sensitivity, approximately in proportion to the square of the length, but no great improvement is obtained

by increasing its diameter beyond the point where the dimension-ratio ceases to be a large number. Sensitivity will also depend upon sensitivity of the galvanometer and the number of turns upon the secondary coil.

Some difficulties are experienced owing to the fact that the two halves of the permalloy are not truly identical. To some extent this is eliminated by means of the reversing-switch in the primary circuit. It is important that the position of the entire assembly--permalloy core, secondary coil, and neutralizing-coil--be kept in fixed relation to each other. The device is free from deleterious effects due to exposure to strong magnetic fields because of the fact that the permalloy is taken through a complete saturation-curve, which wipes out any "memory" of its previous magnetic experience.

To a considerable degree the deflections of the galvanometer obtained when the snap-switch is manipulated are proportional to the constant field to which the sensitive element is exposed. Closing the snap-switch produces a deflection of one sign, regardless of the position of the reversing switch, while opening the snap-switch produces a deflection of the opposite sign. If the sensitive element is inverted in the field, the signs of these deflections are reversed. For rough measurements sensitivity of the galvanometer may be reduced and its deflections may be taken as a measure of the field.

The most accurate results are obtained by using the sensitive element as a null-detector and taking the strength of the neutralizing-current as a measure of the field. Employing convenient sizes and constants for the sensitive element, sufficient sensitivity can be developed that the best meters are not adequate for reading the neutralizing-current. Improved accuracy should be obtainable by using a potentiometer for measuring the neutralizing-current. Since the sensitive element is independent of gravitational effects and responds only to the component of the field along its axis, the instrument can be mounted on a support with two degrees of rotational freedom and used as a universal magnetometer for measuring H, Z, and F, and, by null methods without passing a current through the neutralizing solenoid, D and I as well. Application of the device for this purpose, together with the results obtained with it are described in the paper by R. E. GEBHARDT which follows this one (see pp. 53 - 58).

A number of possible variations in the instrument should be noted. For example, the primary could consist of two separate windings side by side with separate pieces of permalloy wire mounted in each of them. It would also be possible by mechanically operating the switching-circuit and an appropriate rectification in the secondary circuit to obtain continuous records of changes in the field.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

T. A. JAGGAR: Volcanoes declare war: Logistics and strategy of Pacific volcano science, Paradise of the Pacific, Ltd., Honolulu, 166 pp., 39 pls., 34 figs., 1945.

(Published by permission of the Director, United States Geological Survey, Department of the Interior.)

The book is well printed in double-column quarto format. A 32-page middle section contains many beautiful half-tone illustrations of volcanic subjects; five full-color illustrations include an exceptionally fine view of the lava fountains in Mokuaweoweo caldera during the eruption of 1940 of Mauna Loa, Hawaii, by P. E. Schulz, reproductions of paintings of Mauna Loa eruptions by D. H. Hitchcock, and of Parícutin by W. Twigg-Smith.

Dr. Jaggar's long experience as resident volcanologist at Kilauea, and many field excursions to other volcanic areas, supply a wealth of volcanological information which is combined with material from the writings of others to present a dramatic picture of present-day central- and circum-Pacific volcanism. The book is prepared, not for the geologist or volcanologist, but for the layman. As the author states in his introduction, "the volume is not a textbook and presents no histories of each locality. It is designed to show the educated layman pictures . . . . of nature's fireworks. It exhibits, sometimes startlingly, events that were startling." The purpose of practical volcanology is well stated, by one of its leading exponents, to be the prevention or amelioration of disaster, "to help humanity, if possible, in protection, in foresight, and in common-sense knowledge."

Starting in the central-Pacific, with descriptions of the 1924 and 1934 eruptions of Kilauea and the 1935 eruption of Mauna Loa, in Hawaii, the discussion shifts southward to Niuafoou, Falcon Island in the Tonga Group, and on to New Zealand, with accounts of the activity of White Island and the 1886 eruption of Tarawera. Thence the reader is taken in a clockwise direction entirely around the Pacific, by way of the Rabaul eruption of 1937; Krakatoa and Anak Krakatoa; Tomboro in Sumbawa; the Javanese volcanoes, Batur in Bali, Rokatinda just north of Flores; Taal and Mayon in the Philippines; Sakurajima in Japan; the Kamchatkan volcanoes; Bogoslof, Katmai, Dana, and Pavlof volcanoes in Alaska; the Cascade volcanoes and the 1915 eruption of Lassen Peak; the "Geysers" area near Calistoga in California; Parícutin, and the volcanic and seismic areas of Central America and the Andes; to end with a description of the great eruption of 1902 at Mount Pelee in Martinique. Interesting sidelights on the author's career are supplied by accounts of bear-hunts in Alaska and the operation of Jaggar's pioneer amphibian boat. Little of the material is new, but it is gathered together from a wide range of sources, some more or less obscure, and combined in a form readable by the layman.

From the standpoint of the interested layman, much of the book is well done, though there are places at which the inclusion of controversial or highly technical material (despite the author's introductory promise to avoid "abstruse science") may result in misconceptions on the part of those with insufficient background in volcanology to permit judicious weighing of such statements. The inclusion of a glossary of technical terms is in itself a commendable feature, but it is doubtful whether the reader will be aided by such definitions as those of agglomerate as "volcanic puddingstone," augite and hypersthene as "a dark magnesian mineral," basanite and tephrite as "a feldspar basalt," and "nuées" as "Pelee glow clouds moving down rift." Some of the terms would have been better avoided altogether in a book designed for the layman.

Despite its popular character, the geologist and volcanologist will find the book a convenient source of information on eruptions in the areas listed above. It is regrettable, however, that the text was not brought up-to-date before publication. Several of the chapters were written wholly or in part many years ago, for other publications, but there is no evidence of any general attempt at modernization for the present volume. Regrettable also is the retention of Hodge's "Mount Multnomah," the great ancestral peak of the Three Sisters Region, Oregon, despite Williams' recent convincing demonstration of its purely mythical character.

Jaggar's experience with the phreatic explosions of 1924 at Kilauea leads him to a reconsideration of volcanic explosions in general, with conclusions which are decidedly at variance with accepted volcanologic theory. Probably few volcanologists will agree with his characterization of the 1822, 1906, and 1944 eruptions of Vesuvius, the violent explosions of Mount Pelee, Santa Maria, Katmai, Anak Krakatoa, and those which accompanied the collapse of Crater Lake caldera, as phreatic steam-blasts. Indeed, the great predominance of new magmatic material ejected during those explosions appears to make such a conclusion quite untenable.

Jaggar's belief that aerial bombing of the flow caused cessation of lava extrusion at Mauna Loa in 1935 appears based on entirely insufficient evidence. Certainly the stopping of extrusion a few days after the bombing, in a single instance, cannot be regarded as conclusive. Moreover, the explanation of the mechanism by which the bombing is supposed to have caused the stoppage is unsatisfactory. The author says that as a result of bombing of the main pahoehoe tube, a considerable distance below the vent, "the equilibrium of self-heating was destroyed and the slag, after spilling over for two days, stiffened, slowed down, and solidified into the source vent." Even if heating by exothermic reactions is accepted, and this is by no means conclusively demonstrated, the manner in which local bombing of the tube could cause a cessation of such reactions back along the tube and down into the vent is far from clear.

Such criticisms from the viewpoint of the volcanologist, of a book directed to the layman, are perhaps unwarranted. The effort to interest the general public in volcanoes is most certainly to be commended.

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Transactions, American Geophysical Union | Volume 27, Number I | February 1946

AN INDUCTION-MAGNETOMETER--CONSTRUCTION AND TESTS

R. E. Gebhardt

Abstract--Constructional details and results of tests of an induction-magnetometer for measuring all components of the geomagnetic field are discussed. Standardization through preliminary base-line values at the Cheltenham Magnetic Observatory, obtained with the Carnegie Institution of Washington sine-galvanometer, show only small corrections to the computed constants in all elements. Largest corrections appear in Z and F. If base-line values are obtained by the induction-magnetometer and the magnetograms used only to tie in measurements of different elements, the value of F as observed differs by only two gammas from that computed from the observed values of H and Z.

General statement

Magnetometer--The principles of the magnetometer were described by McNISH in the preceding paper (see pp. 49 - 51). As he stated, the search-coil of the magnetometer consists essentially of three concentric coils: the primary, neutralizing, and secondary. The unit is mounted in such a way that the coil may be oriented in any direction about two axes at right angles to each other.

In order to expedite the construction, the base, horizontal circle, standard, and vertical circle of a special GURLEY, nonmagnetic engineer's transit was used. The search-coil was mounted in a brass case with new trunions so constructed and lapped as to fit the wyes of the transit. The over-all length of the search-coil was limited to a size that would transit through the standard. Slight modifications in the original design were required in order to shorten the coil and maintain the sensitivity desired in the completed instrument.

Control-box--The control-box consists of a potentiometer, galvanometer, several standard resistances, and miscellaneous switches, variable rheostats, and keys to perform the desired operations and obtain the precision in current-measurements necessary to maintain the desired accuracy of ten gammas in the final results.

FRANK WENNER, formerly of the National Bureau of Standards, was consulted on the design of the controls. The potentiometer incorporates several novel features that permit measurement of the emf across the standard resistances by measurements of the difference of the emf of the standard cell and the drop across the resistances.

The galvanometer is arranged so that it may be used in the secondary-circuit for reaching a balance and then, with the potentiometer, to measure the drop across the resistances. A group of fifteen standard resistances are arranged under a contact-switch to permit measurement of magnetic fields from 0 to 800 milligauss. Several variable rheostats are also provided to adjust the current in the primary-coils and the neutralizing-circuit.

Constructional details

Magnetometer--A schematic diagram of the arrangement of the three coils in the brass housing is shown in Figure 1. The primary-coil consists of four individual coils wound on copper forms. The coils are connected in series so that every other coil has the opposite polarity and has a permalloy rod inserted in each. The coils as constructed are wound with no. 28 gage single cotton-covered copper wire. The resistance of each individual coil is approximately 0.545 ohms. The four coils were taped together and slipped inside the form for the neutralizing-coil.

The neutralizing-coil is a single layer solenoid of no. 20 single cotton-covered, enameled copper wire having approximately 10.6 turns per centimeter. In order to minimize the end-effects, ten extra turns were added in three layers near the ends. The resistance of this coil is 0.387 ohms.

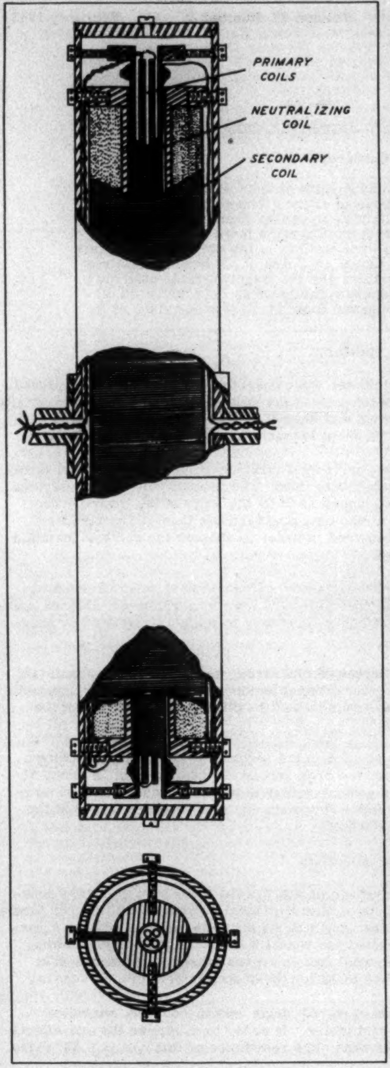

Fig. 1--Sectional view of search-coil assembly of induction-magnetometer

The secondary-coil consists of 49720 turns of no. 33 enameled copper wire. It is layer-wound, the individual layers are insulated with .0015 inch onion-skin paper, and has a resistance of 2982 ohms.

The brass tube and housing for the search-coil was made from tested nonmagnetic brass. The brass end-caps were fitted with special removable peep-sights so that the telescope mounted below the coil could be collimated with the axis of the coil. The telescope was added to permit observations for the magnetic declination by referring to a known azimuth-line. The design finally adopted may be used for observations of declination, horizontal intensity, vertical intensity, inclination, and total force. The assembled magnetometer is shown in Figure 2.

Control-box--The control-box was built by contract. The arrangement of switches, tap-keys, dials, and other elements, was decided on after expert advice on the position for most convenient operation. The design finally adopted has proved very efficient and exceptionally convenient for rapid operation. For operation the galvanometer is connected directly to the secondary coil and the variable resistances adjusted until the field inside the neutralizing-coil or solenoid exactly balances the component of the Earth's field being measured. The galvanometer is then used with the potentiometer to measure the potential-drop across standard resistances of a selected value. The control is so arranged that the standard cell can be placed in opposition to the drop across the standard resistances and the difference measured on the potentiometer.

An abridged schematic wiring diagram of the electrical circuit is shown as Figure 3. The top view of the control-box and an oblique view of the box are illustrated in Figures 4 and 5.

Balancing the coils--After the magnetometer was constructed, one of the most interesting tasks encountered was that of cutting the stock lengths of permalloy. As the material had been annealed for the best magnetic properties by the manufacturers, extreme care was necessary in cutting the material to prevent damage by excessive binding and shear. It was finally decided to set the rods in small channels milled in a brass strip and then to flow warm beeswax into the groove, securely supporting the material throughout its length. The rods were then cut to the proper length and the beeswax dissolved off the rods.

It is most convenient to adjust the position of the permalloy by orienting the search-coil in the prime vertical and observing the setting of the horizontal circle for the primary current direct and reverse. This "split" can be adjusted to zero for any particular saturating-current. After this adjustment had been made the rods were firmly cemented in place.

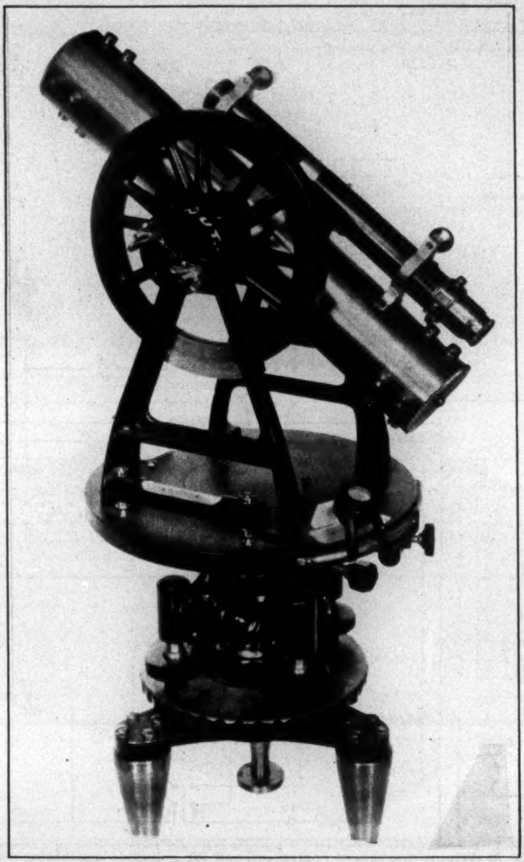

Fig. 2--Search-coil assembly of induction-magnetometer mounted in wyes of engineer's transit

There is also an opportunity to orient the neutralizing-coil by means of one set of capstan-screws, by observing the "split" in readings of the horizontal intensity for the coil in two positions. It was found that the original setting as made in the instruments-shop was within a minute of the proper setting, so that no attempt was made to improve the adjustment.

Determination of constants

The magnetometer was standardized at the Cheltenham Observatory and the value of the coil-constant determined by comparison against the sine-galvanometer.

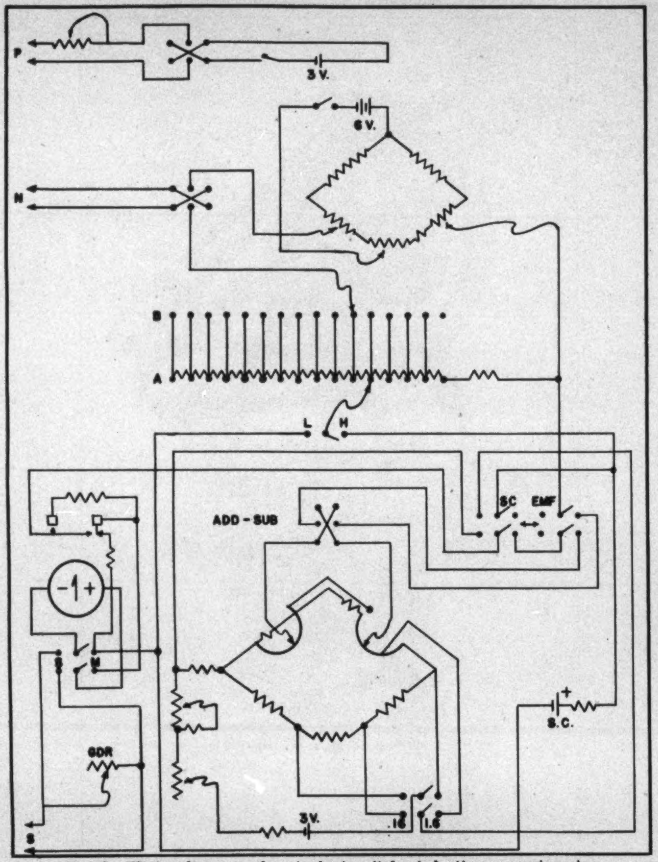

Fig. 3--Wiring diagram of control-circuit for induction-magnetometer

A series of observations was made at room-temperature. Then the temperature of the room was raised slowly and observations made at a higher temperature. Additional observations were made at temperatures considerably below room-temperature. The thirty-seven individual observations covered the temperatures likely to be encountered in the field (13°C to 42°C). From this series it was possible to compute "log C" and also the temperature-coefficient of "log C." The equation for the field inside an infinitely long solenoid is $H = 4\pi ni/10$, where i is in international amperes. This immediately reduces to the value $H = Ci$ or $H = CE/R$.

The value of log C computed from the physical dimensions of the neutralizing-coil is 6.1261. The value as determined through comparison with the sine galvanometer is 6.12647 at 20°C. The

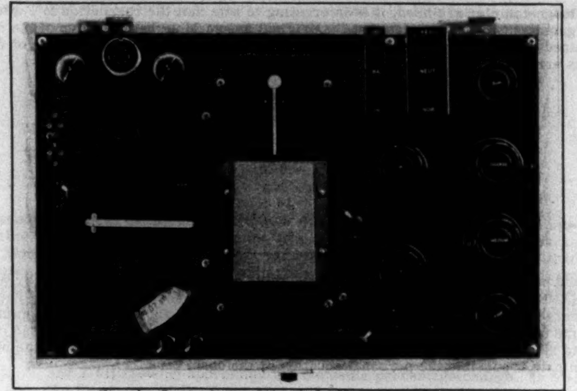

Fig. 4--Control-panel for induction-magnetometer

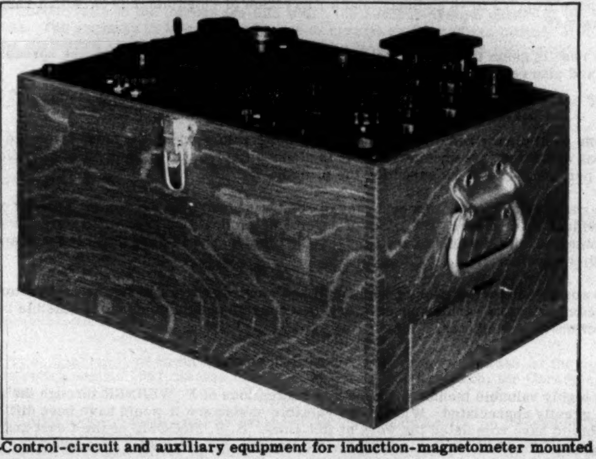

Fig. 5--Control-circuit and auxiliary equipment for induction-magnetometer mounted in box

average value of the temperature coefficient of log C in the range 13° to 42° centigrade was found to be -0.000013.

Standardization-observations

In addition to the observations outlined above an independent series of standardization-observations were made for declination, horizontal intensity, vertical intensity, inclination and total force. The original series consisted of four observations for each element by each of two observers. The results of the standardization-observations are summarized in Table 1. These results are all computed through the sensitive magnetograph at the Cheltenham Observatory, assuming the observatory base-lines, obtained with the Carnegie Institution of Washington sine-galvanometer for H, to be correct. The results are based on preliminary base-line determinations and are subject to some modification and revision after adjustment. If the base-lines determined by the induction-magnetometer are used, it is interesting to note that the correction to F reduces to about two gammas, which indicates that the original assumption that the value of the coil-constant as determined through the sine-galvanometer can be carried to the determination of Z and F without serious error.

Table 1--Standardization-observations of induction-magnetometer based on preliminary Cheltenham base-lines

Element	Correction	Range
D	+ 0′.5	+ 1′.0 to - 0′.3
H	+ 1 γ	+11 γ to - 5 γ
Z	+14 γ	+30 γ to + 2 γ
I	- 0′.06	+ 0′.33 to -0′.66
F	+11 γ	+25 γ to - 1 γ

It should be noted here that the two geophysicists assigned to the project, C. E. WESTERMAN and A. J. HANNERS, alternated on the control-box and setting the magnetometer. Their individual average corrections differ by a small but consistent amount of about two to three gammas. The spread of the observations in Z and H were a little larger than desirable, and it was considered advisable to alter the observing-procedure in the hope of reducing the spread of the observations and to eliminate, if possible, the personal equation of the observers.

The result of the second series using this improved procedure gave a correction of zero in H with a range from +3 to -6 gammas, and a correction of +6 gammas in Z, with a range from +9 to +1 gammas.

The results seem to indicate that the improved procedure will reduce the spread of the observations and also reduce the personal difference first noted.

Conclusions

These preliminary results, obtained at the observatory under the most favorable observing conditions are extremely encouraging. It is planned to give the instrument a short field-trial as soon as personnel can be released for the project.

The results indicate that an accuracy of somewhat less than ten gammas can be expected in any individual observation. The mean of several determinations has slightly greater accuracy than is obtained with the customary field-magnetometer, and is considerably more accurate than the Earth-inductor.

The absolute determination of horizontal and vertical intensity and the satisfactory transfer or intercomparison of various observatory-instruments seems much more feasible by means of the induction-magnetometer.

Acknowledgments

The highly valuable technical advice and suggestions of F. WENNER through the entire project are greatly appreciated. Without his valuable assistance it would have been difficult if not impossible to have completed the work at this time. H. E. McCOMB of the Coast and Geodetic Survey started the work on the instrument and worked with the author throughout the entire project. C. E. WESTERMAN and A. J. HANNERS spent a month in calibrating the equipment and making the extended series of observations reported here. The search-coil assembly was constructed and mounted by DAVID WARK in the instrument-shop of the Coast and Geodetic Survey.

U. S. Coast and Geodetic Survey,
Washington, D. C.

(Manuscript received May 29, 1945; presented at the Twenty-Sixth Annual Meeting, Washington, D. C., May 31, 1945; open for discussion until July 1, 1946.)

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DIURNAL VARIATION ANOMALIES AT TUCSON

W. J. Rooney

Abstract

The seasonal changes in diurnal variation at Tucson, Arizona, are of unusual interest because of its location in the transition-belt where the type of diurnal variation changes markedly during the year. Monthly hodograms of the diurnal variation in Earth-current potential-gradient indicate that its changes are generally consistent with the recognized movement of the current systems in the ionosphere northward and southward with the sun. Two definite anomalies, less readily explained, are found to exist. The first is a marked increase in activity in January, which appears as a large increase in amplitude, and the second consists of a decrease and irregularity in the eastward component during March. Corresponding anomalies are found in the magnetic diurnal variation. In January that of the total force, F, is increased to a value well above its mean winter-level with X, Y, and Z all showing approximately the same percentage-change. In March only X is abnormal, and, like the eastward Earth-current component, its diurnal variation is small and irregular. The winter anomaly might be accounted for by assuming the existence of a zone of unusually high conductivity in the ionosphere into which the current-system passes at its southernmost position. The anomaly in March may be due to erratic shifting of the latitude of the current center to the northward similar to the shifts deduced by HASEGAWA from the records at Japanese stations.

[Note: The complete paper was published in the September, 1945, number (Volume 50) of Terrestrial Magnetism and Atmospheric Electricity, pp. 175-184.]

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

(Abstract received June 16, 1945; complete paper presented at the Twenty-Sixth Annual Meeting, Washington, D. C., May 31, 1945.)

NOTES AND PERSONALIA

(See also pp. 14, 48, 60, 68, 107, 110, 118, and 120)

PERSONALIA

Frederic E. Clements, of Santa Barbara, California, died on July 26, 1945, at the age of 70. Prior to his retirement in 1941, he was in charge of Ecological Research, the Carnegie Institution of Washington.

Gilbert Colfax Dobson died, after an extended period of poor health, on December 29, 1945, at his home in Tulsa, Oklahoma, at the age of 64. Prior to his retirement in 1943, he was Chief of the Sedimentation Division, Office of Research, Soil Conservation Service, and in this position contributed actively to the developments in that field. Previously he was engaged on flood-control work with the Corps of Engineers. He served in World War I, attaining a rank of Major. Earlier he had been engaged on engineering work in the Philippine Islands and the Canal Zone.

Homer D. Erwin died from a sudden illness on September 10, 1945, at the age of 41. His brief professional career had taken him on important geophysical and geological work in Bolivia, Mexico, Honduras, as well as various parts of the United States. During the War he had been engaged in studying the occurrence and distribution of vanadium. Among his avocations were high-altitude climbing and exploration of glaciers.

Belated word has been received of the death of Milton H. Schoerpner at Longvy, France, on September 12, 1944, at the age of 27. Prior to his entry into the Army in September, 1943, Mr. Schoerpner was Junior Hydraulic Engineer with the United States Geological Survey at Albany, New York, and at the time of his death, he was attached to the Headquarters Company, 1194 Engineer Base Depot Group.

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 68, 107, 110, 118, and 120)

PERSONALIA

R. C. Farrow has returned from service as a Major in the Canadian Army in the European Theatre, and has again taken up his duties as Chief Hydraulic Engineer, Water Rights Branch, Department of Lands and Forests, Government of the Province of British Columbia.

H. Richard Gault has accepted an appointment as Assistant Professor in Geology at Lehigh University beginning February 1. He has been with the Alaskan Branch of the United States Geological Survey since May, 1942, and will continue this association on a part-time basis.

L. Standish Hall, East Bay Utility District, Oakland, California, has been awarded the *Karl Emil Hilgard* Prize by the American Society of Civil Engineers for his paper entitled "Open channel flow at high velocities."

Arthur W. Harrington, District Engineer of the United States Geological Survey on surface-water investigations in New York, has been elected one of the Vice-Presidents of the American Society of Civil Engineers.

H. W. Hemple was appointed Chief of the Division of Geodesy of the United States Coast and Geodetic Survey on October 1, 1945. He had served as Assistant Chief of that Division since August 1, 1938.

H. H. Hess expects to return to Princeton University in April to resume teaching there. Commander Hess has spent two years on duty in the Pacific, which afforded him brief glimpses of many of the islands.

George T. Hickox, Hydraulic Engineer with the Tennessee Valley Authority, has been awarded the *J. James R. Croes* Medal of the American Society of Civil Engineers for his paper entitled, "Aeration of spillways."

W. W. Horner, Hydrologist and Consulting Engineer of St. Louis, Missouri, has been elected President of the American Society of Civil Engineers.

Earl Ingerson of the Geophysical Laboratory, Carnegie Institution of Washington, has returned from a three-month sojourn in Brazil and other points in South America. He visited the principal quartz-producing districts in Brazil, and made collections in each district for laboratory study. He also studied the collections of quartz crystals in Buenos Aires and Santiago, visited the copper mines and nitrate deposits in Chile and the tin mines in Bolivia, and studied areas of volcanic and tectonic interest near Arequipa, Peru. He stopped at Parícutin in Mexico on his return trip.

R. H. Johns of the United States Geological Survey has been appointed to fill a vacancy in the staff of the Division of Geological Sciences at California Institute of Technology. He will succeed *H. J. Fraser*, who has joined the staff of the Falconbridge Nickel Company.

Raphael G. Kazmann, formerly with the United States Geological Survey, is now with Ranney Method Water Supplies of Louisville, Kentucky, in charge of water-supply investigations.

George C. Kennedy has resigned from the Naval Research Laboratory, where he was engaged in experiments on growing piezoelectric crystals. He is now a Junior Fellow of the Harvard Society of Fellows, at Harvard University, working on crystallization from silicate melts at high pressure.

James B. Macelwane of the Institute of Geophysical Technology, St. Louis University, presented an address over the Columbia Broadcasting System network January 13, in connection with the philharmonic-symphony concert of the United States Rubber Company. The subject of Father *Macelwane's* talk was "Forecasting earthquakes."

Hugh C. Mitchell, Principal Mathematician in the Division of Geodesy, United States Coast and Geodetic Survey, retired on November 30, 1945. Mr. Mitchell entered the Bureau in 1898. During recent years he has been very active in developing interest in the State Plane Coordinate Systems. It has been mainly through his efforts that 19 states have adopted the systems legally for use in the description of property boundaries.

C. L. McGuinness of the United States Geological Survey has been assigned to make a reconnaissance survey of the ground-water resources of Puerto Rico.

F. B. Plummer, Professor of Petrology at the University of Texas, has recently been elected President of the Texas Academy of Sciences.

Transactions, American Geophysical Union Volume 27, Number I February 1946

SOME OBSERVATIONS ON WATER-LEVELS AND OTHER PHENOMENA ALONG THE BOSPORUS

Waldo E. Smith

Abstract--The flow in the Bosporus is normally from the Black Sea to the Sea of Marmara. This occurs a high percentage of the time. Data gathered in connection with this study show that a drop from the Black Sea to the Sea of Marmara up to 1.5 feet or even more produces this flow. Occasionally, however, due to the effects of strong south winds, there is a reversal of the gradient, and the flow is from the Sea of Marmara to the Black Sea. Possibility of density-currents, caused by the differences of salinity of the Black Sea and the Sea of Marmara, is touched, and other phenomena related to the Bosporus are mentioned briefly.

Introduction--The Bosporus is a thread of living blue water about 20 miles long (see Fig. 1) connecting the Black Sea and the Sea of Marmara, and flows normally north to south, from the

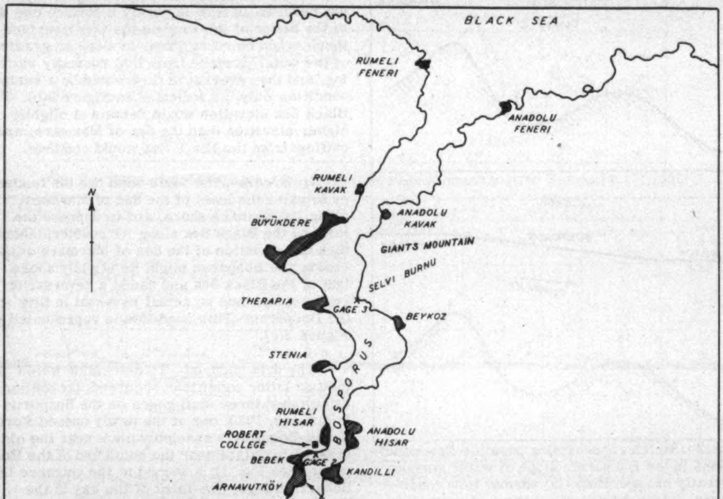
BLACK SEA
RUMELI FENERI
ANADOLU FENERI
N
RUMELI KAVAK
ANADOLU KAVAK
BÜYÜKDERE
GIANTS MOUNTAIN
SELVI BURNU
THERAPIA
GAGE 3
BEYKOZ
STENIA
BOSPORUS
RUMELI HISAR
ROBERT COLLEGE
ANADOLU HISAR
BEBEK
GAGE 2
KANDILLI
ARNAVUTKÖY
AKANTI BURNU
ORTAKÖY
EYOUB
PERA
GOLDEN HORN
GALATA
GAGE 1
ÜSKÜDAR
STAMBOUL
ARM OF ST. GEORGE
ISTANBUL
HAIDAR PASHA
SEA OF MARMARA
SCALE IN MILES
0
2
4
6
8
10

Fig. 1--Map of the Bosporus vicinity

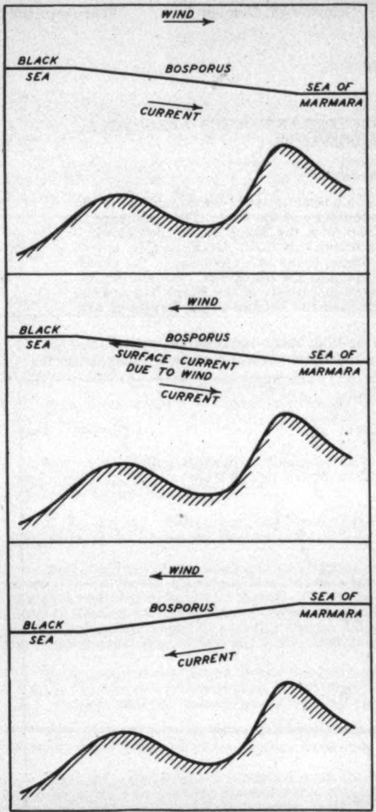

Fig. 2--Sketch representing possible flow conditions in the Bosporus, slope of water surface greatly exaggerated--(a) normal flow conditions, (b) conditions of reversal of surface-current with no reversal in gradient, (c) condition of flow with reversal in gradient

Black Sea. The surface-current is frequently swift and the water is usually sparkling and clear. Tide-effects on these land-bound waters are very small. Through the major portion of the year, winds along the Bosporus are generally north to south in direction but occasionally there is a wind-shift and the wind may blow from the south for several days. After one or two days of such wind, there is a noticeable slowing of the surface-current in the Bosporus, and if the wind is strong, finally a reversal in direction of the current, at least as far as the surface-indications are concerned, and the Bosporus then appears to flow from south to north.

The problem--Normal flow-conditions in the Bosporus are represented by Figure 2(a), showing a slightly higher elevation of water surface in the Black Sea than in the Sea of Marmara, thus inducing flow from the Black Sea.

In the event that the phenomenon of apparent reversal in flow is purely a surface one due to the action of the wind on the water-surface, there would be no reversal in slope or gradient of the water-surface from that normally occuring, and the reversal in flow would be a surface-condition only, as indicated in Figure 2(b). The Black Sea elevation would remain at slightly higher elevation than the Sea of Marmara, and outflow from the Black Sea would continue.

If, however, the south wind has the tendency to raise the level of the Sea of Marmara along its northern shore, and to depress the level of the Black Sea along its southern shore, then the elevation of the Sea of Marmara adjacent to the Bosporus might be slightly above that of the Black Sea and cause a reversal in gradient and thus an actual reversal in flow in the Bosporus. This condition is represented by Figure 2(c).

The data secured--To determine which of the two latter conditions occurred, the author established three staff-gages on the Bosporus in January, 1930; one at the newly opened Ford Motor Company's assembly-plant near the old arsenal in Galata near the south end of the Bosporus (see Fig. 1); a second at the entrance to Robert College, one-third of the way to the Black Sea; and a third on the Asiatic shore of the Bosporus at the Standard Oil plant at Selvi Burnu, about two-thirds of the way from the Sea of Marmara to the Black Sea. The gages were attached to quay-walls or piers and were exposed to the wave-action and surges at these points. They were maintained until the author's departure from Constantinople in June, 1931.

Datum was established on the gages by levels that were run from nearby bench-marks of the city-datum, but no line of levels was run directly from gage to gage, nor is the relationship of the datums on the two sides of the Bosporus known. Thus errors and differences in the city-datum are inherent in the data here presented. These appear to be small.

The gages were ordinarily read at about 8^h and 17^h by volunteer observers, who usually recorded wind-direction, calmness or roughness of the water, and the direction of flow at the surface. The author also made notes on direction of water-movement at critical times. No attempt has been made to secure weather and other records that may be available in Turkish archives; the data at hand appear to be sufficient to provide an answer to the question raised.

With visual observation on the staff-gages and without synchronization of the observations, there are undoubtedly errors in the data, but these apparently are not of sufficient magnitude to preclude the answering of the question, though at times there is gross inconsistency. The author suspects that in some few cases an observer may have inserted an "estimated" reading at a time that the gage was forgotten. The bulk of the readings are, however, quite consistent. The data for the two major critical periods during which records were kept are given in Figures 3 and 4. These show that under the prevailing conditions, the gradient between gages 3 and 1 has one-half foot to a foot of drop going from north to south, thus providing the energy to produce the usual flow to the Sea of Marmara. With the occurrence of south wind, the gradient tends to flatten considerably, and occasionally there is a reversal in it, as indicated on February 3 and 4, 1930, October 7 and 8, 1930, and at other times.

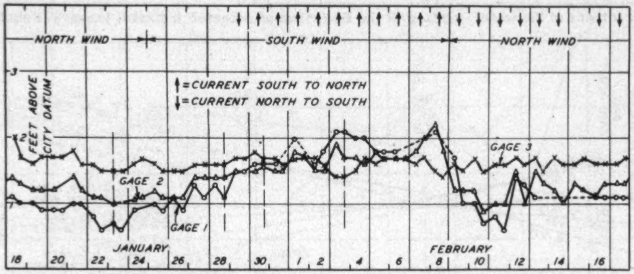

Fig. 3--Stage-hydrographs for the Bosporus gages, January 18 to February 17, 1930

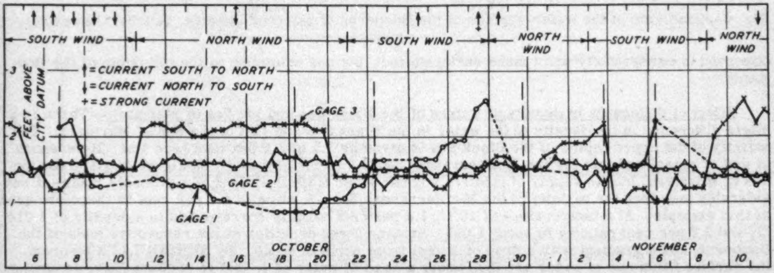

Fig. 4--Stage-hydrographs for the Bosporus gages, October 5 to November 11, 1930

To show this effect more clearly, representative gradients are shown in Figures 5 (relating to the period shown in Fig. 3) and 6 (relating to the period shown in Fig. 4). These gradients are for the observations shown by the vertical dashed lines on Figures 3 and 4, and have been extended beyond the limits of the gages for convenience in labeling only.

Observe, on Figures 3 and 4, that the water-level for gage 2 usually lies between that for gages 1 and 3, as it correctly should. The occasions on which this is not the case can only be accounted for by error, some possible sources of which were previously noted. Gage 1 was quite exposed to wave-action from the Sea of Marmara, which, on south-wind days was especially bad. Such recordings as those on October 28, 1930, can probably be attributed to that difficulty. The data are convincing, however, in demonstrating that a reversal in gradient occurs, and that the reversal in flow

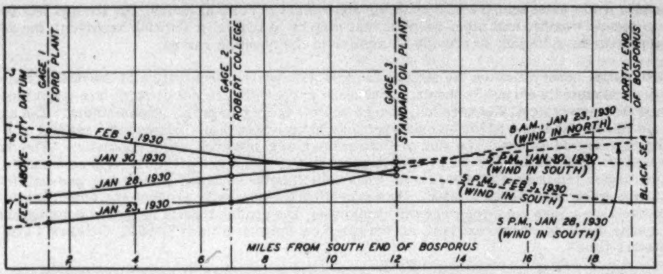

Fig. 5--Gradients of the water-surface of the Bosporus at selected instants, January-February, 1930

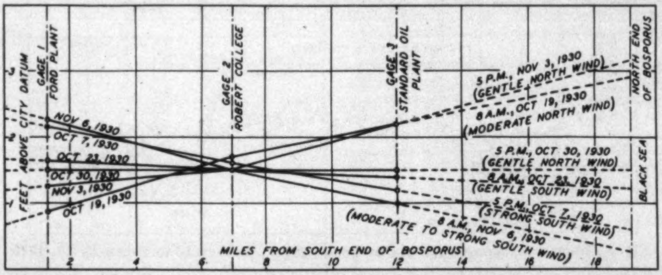

Fig. 6--Gradients of the water-surface of the Bosporus at selected instants, October-November, 1930

observed is consequently not a mere surface-effect, but one extending to the full depth of the Bosporus.

Effect of difference in density of waters of the Black Sea and the Sea of Marmara--There is a slight difference in the density of the water in the Black Sea and that of the Sea of Marmara. The salinity of the upper depths of the Black Sea is given as 1.5 to 1.8 per cent [see 1 of "References" at end of paper] and that for the Mediterranean Sea 3.7 to 3.9 per cent. No figure is given for the Sea of Marmara, but its supply of relatively fresh water from the Black Sea probably makes it considerably less than the salinity of the Mediterranean Sea. A value of 2.8 per cent is therefore used in this example. At a temperature of 10°C, 1.8 per cent salinity corresponds to a density of 1.014 [2] and 2.8 per cent salinity to about 1.022. Assume these densities at the respective ends of the Bosporus, and a gradient with a drop of h feet from north to south. By BERNOULLI'S theorem, the surface filaments of water are thus under a head of water of h feet to produce flow, assuming the velocity to be zero in the Black Sea and Sea of Marmara. The differential in pressure intensity in feet of water, or the head of water producing flow at any depth h_1 at the south end, is $h_f = 1.014 (h_1 + h) - 1.022\ h_1$. If h, the gradient drop, is 1.5 feet, the head producing flow h_f becomes zero when $h_1 = 190$ feet, and below that depth, h_f is negative, indicating that the pressure-differential would favor flow foward the Black Sea.

The maximum depth in cross sections varies from 120 feet [3] at the shallower south end to about 220 feet at the north end, with depths up to 400 feet in the constricted reach at gage 2. The depth at the southern end would seem to preclude the possibility of underflow from south to north with the gradient assumed.

If, however, the gradient has a drop of but 0.5 feet, and the densities are as assumed before, the depth of equality in intensity of pressure is about 63 feet, and below that depth, the intensity of pressure would favor a density-current from south to north. However, with the mixing that is bound to occur in the Sea of Marmara and in the 20-mile tortuous channel, it seems unlikely that

there would be underflow into the Black Sea until the gradient becomes even flatter. There may in all cases, however, be a slowing of the north to south velocity with increase in depth, with the maximum velocity occurring at or near the surface. Conversely, under conditions of reversal in gradient (h is negative), velocity may occur at considerable depth. It was the author's unfulfilled plan to carry on further investigations in this connection, utilizing a fixed boat and a weighted bottle with a fin attached, containing a compass floating on slow-congealing wax. This could be lowered into the water and, by the position at the time of congealing, the direction of the current could be established, as suggested by Figure 7.

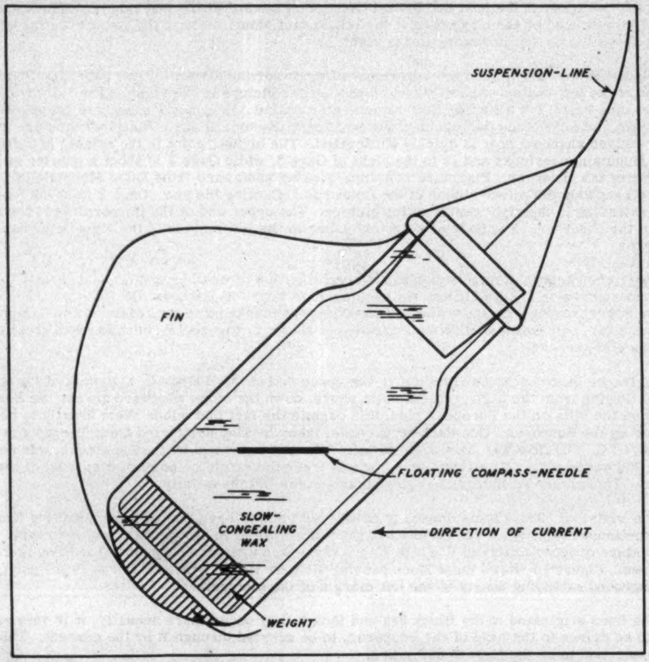

Fig. 7--Suggested device for determining direction of deeply submerged flow

Magnitude of surface velocities--The velocities are, of course, the greatest at the most constricted points of the Bosporus. At the narrowest point near Rumeli Hisar, the width is about a half mile and the depth nearly 400 feet. The velocity past the points or promontories in the vicinity of the gages is considerable. At Akanti Burnu (Point of Currents), the author took surface-observations on a number of occasions. On February 6, 1930, at 13^{h}30^{m}, and on February 7 at 16^{h}20^{m}, it was observed to be about 2.5 feet per second in a northward direction. On February 10, 1930 at 13^{h}30^{m} and on February 13 at 13^{h} it was observed to be about three feet per second southward. At Kandili point, across the Bosporus, on the latter date, at 16^{h}30^{m}, it was observed to be five feet per second. These velocities were taken by timing the movement of floating objects near the quay. Somewhat farther out, velocities appeared to be greater, but it is doubtful if they exceeded six or seven feet per second.

Hypothesis on the reversal of gradient--The author has set up an hypothesis to account for the reversal in gradient, but as this involves data on the Sea of Marmara and the Black Sea that are

not available, no attempt will be made to develop it here. It is based on the cumulative effect of the surface-friction of the wind passing over the water rather than on differential in atmospheric pressure that has sometimes been given as the reason for the "upending" of lakes.

Views of the Bosporus--Figures 8 to 12, inclusive, show views that will facilitate understanding of this paper. In Figure 8 the view was taken from Seraskerat Tower in Stamboul, looking northeast, directly up the Bosporus. The body of water crossed by the pontoon bridge in the left central portion is the Golden Horn. The south end of the Bosporus is off to the right. Gage 1 was located a short distance beyond the bridge. Figure 9 shows the old fortress of Rumeli Hisar between the two trees at the left, and Robert College on the hill at the extreme left. The location of Gage 2 is obscured by the large tree at the left. Giant Mountain is in the remote background directly above the first promontory on the right.

Figure 10 was taken from the uppermost of the towers of Rumeli Hisar (see Fig. 9) showing Kandili at the left center. Akanti Burnu is just off the picture to the right. (The sail-boats are not pleasure-boats, but a fishing fleet returning to market.) Figure 11 shows the choppy water due to current and turbulence that occur at the point near Rumeli Hisar. Note that the wake of the motor-driven charcoal boat is quickly obliterated. The highest point in the remote background, Giant Mountain, overlooks and is to the right of Gage 3, while Gage 2 is about a quarter mile to the rear of the observer. Figure 12 is a view, looking southward from Giant Mountain (elevation 640 feet) showing the silver ribbon of the Bosporus reflecting the sun. Gage 3 is at the foot of the ridge extending to the right center of the picture. The upper end of the Bosporus is to the right rear of the observer. The body of water extending to the left margin of the view is the bay south of Beykoz.

Other phenomena--Every region has its peculiarities of weather and climate, and in these the Bosporus region is rich. It was not uncommon to hear fog-horns on the Bosporus, 300 feet below the Robert College Campus, and see the Bosporus blanketed in fog, while on the Campus the day was clear. An example of this occurrence is shown in Figure 13. Such fog was usually dissipated by mid-morning.

On two or three occasions on trips to the upper end of the Bosporus, a stream of fog was observed flowing from the hills on the Asiatic shore, down the slope westward across the Bosporus and up on the hills on the European side, this despite the fact that winds seem usually to be either down or up the Bosporus. One such occurrence, taken looking northward from Therapia, is shown in Figure 14. The flow was from right to left. The strip covered by the fog-stream was perhaps 150 to 200 yards wide. No attempt was made to trace the origin or point of dispersal of the fog-stream. There were no industries using steam-power in this vicinity.

The winter of 1928-29 was unusually severe with about three feet of snow resulting from almost continuous fall over a period of more than three weeks in late January and February. The temperature dropped nearly to 0°F. In March there was a rare occurrence of ice-floes on the Bosporus. Figure 15 shows these floes passing Rumeli Hisar. (Akanti Burnu is the point of land in background extending nearly to the left margin of the picture.)

The floes originated in the Black Sea and though they occur there annually, it is very rare for them to be driven to the head of the Bosporus, to be carried through it by the current. This occurrence was said to be the first in 350 years.

General weather and climate of the Bosporus are interesting. A narrow belt is said to have two climates. During periods when the wind blows from the north, there is typical, invigorating, temperate-zone weather, and one has zest for work. This prevails perhaps 75 or 80 per cent of the time. When the wind changes to the south, the weather is very enervating and under these conditions approximates a typical eastern Mediterranean climate. That this does not extend very far inland under ordinary circumstances is shown by the fact that in the late fall or early spring of the year one can proceed from the Bosporus over the hills inland three or four miles and find a temperature-drop of a number of degrees, such that ice a quarter of an inch thick may be found on low-lying pools with the temperatures remaining well above freezing at Robert College. In traveling the 20-mile length of the Bosporus, likewise, one may experience great weather changes. It may be raining and quite springlike in Constantinople, and 20 miles north near the entrance of the Black Sea a severe blizzard may be howling. Cloud-formations are frequently unusual. There may be banks to the east, north, and west, with clear weather prevailing over the Bosporus.

Fig. 8--View northward from Stamboul

Fig. 9--View up the Bosporus from Kandili

Fig. 10--View southward from Rumeli Hisar

Fig. 11--View northward, near Rumeli Hisar

Fig. 12--View looking southward from Giant Mountain showing silver ribbon of Bosporus

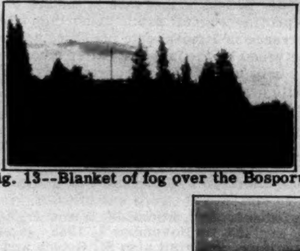

Fig. 13--Blanket of fog over the Bosporus

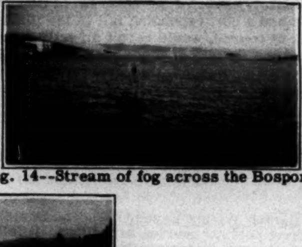

Fig. 14--Stream of fog across the Bosporus

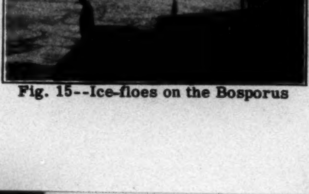

Fig. 15--Ice-floes on the Bosporus

It has been noted that the Bosporus ordinarily is a beautiful blue stream, the like of which is found at few points on Earth. In the event of heavy rain in the immediate vicinity, the small streams dump their burden of water and sediment into the Bosporus. Heavy material is dropped quite soon, but the lighter collodial material is retained in the fresh water and there is to be seen a sharp line of demarcation between the muddy water from the runoff and the blue water from the Black Sea. As the muddy water tends to remain on the surface, this indicates that the fresh water, though cloudy, has a lower specific gravity than the clear salty water of the Bosporus. This was the author's first observation of density-currents.

Acknowledgments--The author is indebted to Mr. RIVA and Mr. SEALANDER of the Ford Motor Company, Mr. SARAFOGLOU of Robert College, and Mr. THOMPKINS and Mr. HARALAMBOPOULAS of the Standard Oil Company for aid in establishing the gages and providing observers, and to KRIKOR MAGHAKIAN for running the line of levels to the gage at the Ford plant.

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[2] THOMAS G. THOMPSON, Physical properties of sea water, Physics of the Earth--V, Oceanography, p. 75, 1932.
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American Geophysical Union,
Washington 15, D. C.

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DISCUSSION

J. B. KINCER (4112 Fessenden Street, Northwest, Washington 16, D. C., December 12, 1945)--As described in this paper, the alternations of weather typical of continental mid-latitude climates, with the milder, more humid sub-tropical type, depending upon the north or south direction of the wind, is interesting, but at the same time such condition is characteristic of regions such as found in the Bosporus environs. Here, north winds frequently bring, from across an extensive continental area, air masses of polar origin, while southerly winds, from sub-tropical latitudes, comprise a mixture of typical Mediterranean and low-latitude arid climates. The contrasts in nearby locations are due largely to the prevailing topography, including attendant "frost pockets," and other physical conditions, such as the influence of contiguous land- and water-surfaces.

With regard to the reversal of flow in the Bosporus, it appears that the author's second hypothesis--a piling up of water, with south wind, along the north shore of the Sea of Marmara, and a corresponding depression in the southern Black Sea, with consequent reversal of gradient--is the most likely cause of the reversal of flow in the Bosporus. In fact, a foot-rise in the sea of Marmara and a corresponding fall in the Black Sea would provide a small south-to-north gradient. This, of course, would result directly from areal difference in atmospheric pressure as the control of the system of winds. This hypothesis is strengthened by the fact that, after a couple of days with south wind, the reversal of flow is gradually built up through a progressive retarding of the north-to-south movement and also is associated with persistent strong south wind.

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 60, 107, 110, 118, and 120)

NOTES

Danish Marine Expedition--The Danish three-masted schooner, Atlantide, is now engaged in the first postwar marine expedition. It left Plymouth, England, on November 1, 1945. It will follow the west coast of Africa all the way to the Cape of Good Hope, and visit also St. Helena and the Ascension Islands, completing the expedition in about eight months. The expedition is primarily one in marine biology and zoogeography and is under the leadership of Anton F. Bruun of the Copenhagen University Museum. Two young Danish zoologists, Jorgen Knudsen and Torben Wolff, and F. C. Fraser of the British Museum and G. R. Howat, British Government chemist, are accompanying him. It is anticipated that much valuable material will be collected for Danish and British museums, as the expedition will visit areas from which little collecting has been done.

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RUNOFF-BEHAVIOR OF SMALL AGRICULTURAL WATERSHEDS UNDER VARIOUS LAND-USE PRACTICES

Harold W. Hobbs

(Miscellaneous Publication No. 38, Contribution No. 1974 of the Maryland Agricultural Experiment Station, Department of Agronomy)

Abstract--A graphic method of studying the frequency of recurrence of runoff peaks has been applied to the short-period records from a number of small agricultural areas. The study shows that for periods as short as two to six years, a consistent pattern of runoff behavior is evident for the data available. The analysis of the data, by this method, for three watersheds in the common three year rotation of corn, grain, and hay, indicates a marked increase in magnitude of runoff peaks where tillage, considerably off the contour, is practiced, compared with contour strip cropping. Where diversion terraces are used in conjunction with the rotation contour cropping, a decrease in the number and magnitude of peak flows is indicated. This is due largely to the channel storage in the terrace which spreads out and reduces the peaks and delays the runoff.

For pastured areas, the data show that the maintenance of good turf on the areas is essential, particularly in winter. The addition of pasture contour furrows definitely changed the runoff pattern and resulted in a marked reduction in runoff for smaller, low intensity rains. For the larger rains, the reduction in runoff by the furrows decreases as the depth or intensity of the rainfall increases.

In general, it appears that short-period records of runoff can be classified on the basis of frequency of recurrence and serve as a guide in making recommendations as to runoff expectancy under similar land managements and conditions. This method of determining the frequency of any runoff magnitude directly is considered superior to other methods where runoff values are first related to the rainfall that produced them, and the determination of runoff frequency is then attempted from rainfall records that are available for longer periods. The advantage of the present method is obvious when it is remembered that rainfall intensity and amount are but two elements in the production of runoff, whereas this method actually measures the distribution of runoff frequencies and takes into account the effect of other watershed characteristics such as length and degree of slope; drainage pattern; size and shape of area; cover; soil type, depth, and condition; and tillage practices. The consistency that is apparent in the plotting of the data indicates that short records may be employed to characterize runoff behavior, and while data for longer periods unquestionably are needed, the direct use of such records should not be overlooked and at present may offer the best method of obtaining usable information.

Introduction--Land-use studies have been under way since 1939 on the Plant Research Farm, six miles northwest of College Park, Maryland. This is a cooperative project between the Agricultural Experiment Station of the University of Maryland and the Research Branch, Soil Conservation Service, United States Department of Agriculture.

Several of the watersheds under study lie adjacent to or near each other, and runoff was recorded for initial periods of about three years under similar practices, after which one unit of a pair or group was changed to a different practice, while the others were continued in the original practice. Results are shown herein for: (1) two adjacent areas and one nearby area (W-I and W-II, and W-V) in a three-year rotation of corn, grain, and hay; (2) two adjacent areas (W-VI and W-VII) in pasture.

Evaluations of intensities of rainfall and runoff have been made by HAZEN'S duration-curve method [see 1 of "References" at end of paper], and plotted on modified logarithmic probability paper. It is realized that the length of records are much shorter than HAZEN recommended for this method. However, due to the often obscure relationships between rainfall-rates and the resulting runoff-peaks, and the immediate necessity of evaluating these short-period records for

field-use and the future planning of the experiments, it has been thought advisable to work with the rates of runoff to determine directly the frequency of their recurrence, rather than try to determine it indirectly in terms of precipitation-frequencies which occurred in the period of record. Furthermore, it is felt that the method can be used in estimating the recurrence of peaks of small drainage-areas in the northern states where a considerable proportion of the runoffs, in fact, sometimes the maximum rate for the year, occurs as the result of snow-melt, or of low-intensity rains on melting snow.

Description of areas--Watersheds W-I, W-II, W-V, W-VI, and W-VII are situated on land that had been in cultivation for many years in truck and general crops, mostly in rectangular fields, with the rows largely off the contour.

In 1938, vegetated diversion terraces were constructed on the areas as shown in the topographic maps, Figures 1 and 2. In 1939, a dividing dike was placed up the middle of the lower area in Figure 1, forming W-I (8.22 acres) and W-II (7.44 acres). Precipitation-station R-1 (automatic recording) was placed on the dike as shown. Runoff-stations consisting of broad crested concrete weirs 16 inches wide with 3:1 crest-slopes [2] were placed at the outlets to each area (see Fig. 3, 1941) and runoff recorded by water-level recorders beginning August 30, 1939. The middle diversion-terrace on the western slope was selected for study and the designated W-V (4.07 acres). An 18-inch drop structure was placed at the outlet of the terrace and the runoff directed through an H-3 sheet-metal flume [2] fitted with a water-level recorder. The grade in the terrace-channel averages 0.6 per cent for the lower 200 feet and 0.4 per cent for the upper 800 feet.

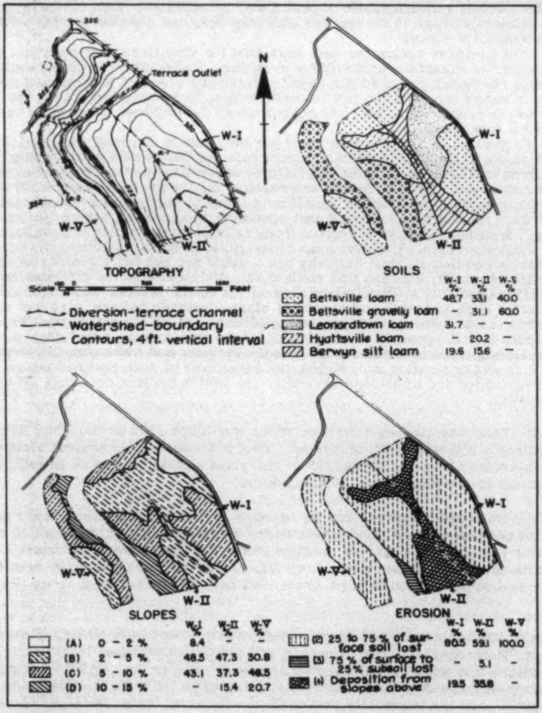
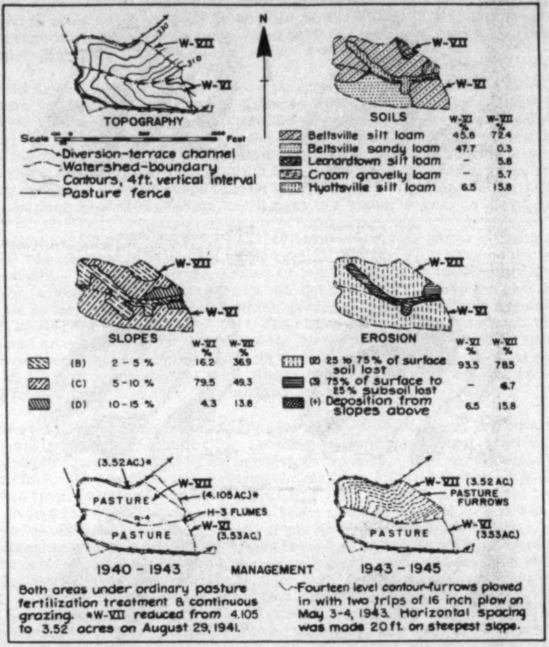

356
Terrace Outlet
N
W-I
W-V
W-II
352
TOPOGRAPHY
Scale 100 0 500 1000 Feet
Diversion-terrace channel
Watershed-boundary
Contours, 4 ft. vertical interval
SOILS
W-I % W-II % W-V %
Beltsville loam 48.7 33.1 40.0
Beltsville gravelly loam - 31.1 60.0
Leonardtown loam 31.7 - -
Hyattsville loam - 20.2 -
Berwyn silt loam 19.6 15.6 -
SLOPES
W-I % W-II % W-V %
(A) 0 - 2 % 8.4 - -
(B) 2 - 5 % 48.5 47.3 30.8
(C) 5 - 10 % 43.1 37.3 48.5
(D) 10 - 15 % - 15.4 20.7
EROSION
W-I % W-II % W-V %
(2) 25 to 75 % of surface soil lost 80.5 59.1 100.0
(3) 75 % of surface to 25 % subsoil lost - 5.1 -
(4) Deposition from slopes above 19.5 35.8 -

Fig. 1--Drainage-area characteristics for areas W-I, W-II, and W-V


N
W-VII
W-VI
330
310
TOPOGRAPHY
Scale 0 500 1000 Feet
Diversion-terrace channel
Watershed-boundary
Contours, 4ft. vertical interval
Pasture fence
SOILS
W-VI % W-VII %
Beltsville silt loam 45.8 72.4
Beltsville sandy loam 47.7 0.3
Leonardtown silt loam - 5.8
Croom gravelly loam - 5.7
Hyattsville silt loam 6.5 15.8
SLOPES
W-VI % W-VII %
(B) 2 - 5 % 16.2 36.9
(C) 5 - 10 % 79.5 49.3
(D) 10 - 15 % 4.3 13.8
EROSION
W-VI % W-VII %
(2) 25 to 75 % of surface soil lost 93.5 78.5
(3) 75% of surface to 25% subsoil lost - 6.7
(+) Deposition from slopes above 6.5 15.8
(3.52AC.)*
PASTURE
(4.105AC.)*
R-4
H-3 FLUMES
(3.53AC.)
W-VII (3.52 AC.)
PASTURE FURROWS
1940 - 1943
MANAGEMENT
1943 - 1945

Both areas under ordinary pasture fertilization treatment & continuous grazing. *W-VII reduced from 4.105 to 3.52 acres on August 29, 1941.

Fourteen level contour-furrows plowed in with two trips of 16 inch plow on May 3-4, 1943. Horizontal spacing was made 20 ft. on steepest slope.

Fig. 2--Drainage-area features and management for pastures W-VI and W-VII

Precipitation-station R-2 (recording) was established at the western edge of the area.

In Figure 3, the general cropping-procedure for these areas is shown. W-I and W-II were laid out in contour-strips of uniform widths of approximately 96 feet. The strips do not vary from the true contour more than two per cent. A rotation of corn, hay, and grain was established on these strips up the slopes in the order given. The area above the diversion-terrace (W-V) was planted to the same crop-rotation in three fields, all rows being within two per cent of the contour. About the same percentage of each crop is in each of the three watersheds each year, but W-V lacks the opportunity for absorption of runoff-water from its cultivated field in grain or hay-strips below, as in W-I and W-II, although there is some absorption of runoff in the terrace-channel bottom. After an initial comparative period (1939-42) during which all three watersheds had had each crop on each field, in other words, a complete rotation had been accomplished, W-II was changed to up-and-down-the-slope tillage in the same three crops. In 1946, it is planned, in continuing this experiment, to put W-I in up-and-down-hill tillage and W-II back in approximate contour-tillage and continue this arrangement through another complete rotation.

The soils, the slopes, and erosion on the three areas are shown in areal extent on maps in Figure 1, together with percentages in each type or class in tables under the maps. These are Coastal Plains soils. The surface soils are somewhat coarser textured on W-II and W-V compared to W-I. The depths of the soil-profiles are somewhat shallower on W-II and W-V compared to W-I.

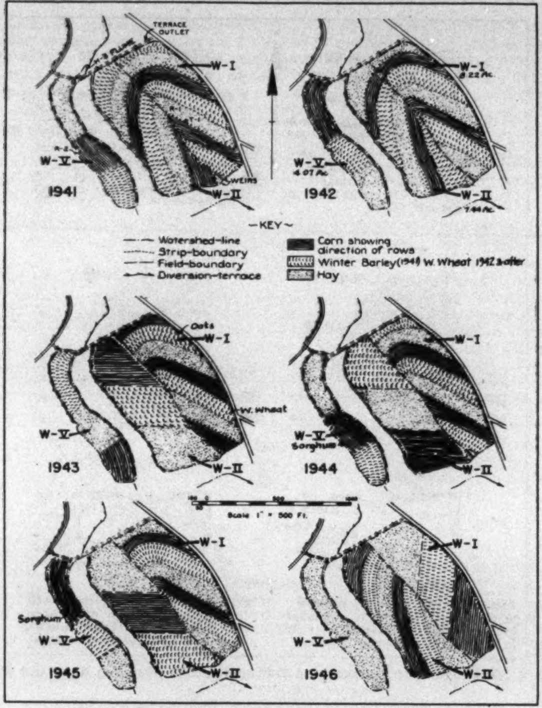

TERRACE OUTLET
W-I
W-V
WEIRS
W-II
1941
W-I
8.22 Ac.
W-V
4.07 Ac.
W-II
7.44 Ac.
1942
-KEY-
Watershed-line
Strip-boundary
Field-boundary
Diversion-terrace
Corn showing direction of rows
Winter Barley(1941) W. Wheat 1942 & after
Hay
Oats
W-I
W. Wheat
W-V
W-II
1943
W-I
W-V
Sorghum
W-II
1944
Scale 1" = 500 Ft.
W-I
Sorghum
W-V
W-II
1945
W-I
W-V
W-II
1946

Fig. 3--Cropping-plan for areas W-I, W-II, and W-V

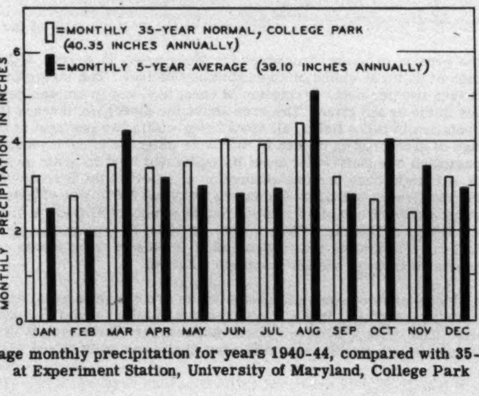


Fig. 4--Average monthly precipitation for years 1940-44, compared with 35-year normal at Experiment Station, University of Maryland, College Park

The depth of soil-accumulation (deposition) from higher-lying slopes is somewhat greater, and the area covered is about twice as great on W-II as on W-I. Both W-II and W-V have steeper average slopes than W-I. The erosion on W-I and W-V has been more extensive than on W-II, but it runs to a higher degree of severity on the latter.

The pastured areas shown in Figure 2 were largely in crops from 1938 to 1940, but were seeded to pasture in 1939 and 1940. Two H-3 flumes were installed at the low points of the areas in the fall of 1940 after constructing a dividing dike down the drainage-way. Precipitation-station R-4 (recording) was placed on this dike near the center of the area. Figure 2 also shows the areal distribution of the soils, the slopes, and erosion-history. W-VII (3.52 acres), in general, has shallower and finer textured soils than W-VI (3.53 acres). Slopes do not average quite as steep on W-VII, but they have a greater range than on W-VI. The extent of erosion is a little greater on W-VI due to a smaller area of deposition, but it runs to a higher degree on W-VII in one corner.

After an initial period of 2.7 years (1940-1943), under ordinary pasture-treatment and management, W-VII was changed in May, 1943 by plowing in 14 pasture-furrows on the contour, W-VI remaining as before. The furrows were formed by two trips of a 16-inch tractor-mounted, two-way plow. First, a shallow furrow was thrown out, but on the second trip the plow was set into the slope four to six inches and much deeper into the ground. Due to prevailing dry weather the furrows were not seeded until the spring of 1944, remaining bare, for the most part, during the first year. Occasional cross-dams were put across the furrows where they were not quite on the contour. The furrows were spaced 20 feet apart on the steepest slope. The vertical spacing varied from 1.3 feet to 3.2 feet, averaging 2.1 feet. Rough computations show that the furrows will take care of runoff from 0.25 to 0.50 inch of rainfall on the area above.

The colluvial Hyattsville and Berwyn soils that occur on these areas are considered to be deep and well-drained, while the Beltsville, Leonardtown, and Croom soil-profiles are generally less well-drained and are underlain by an impervious hardpan, which varies considerably in depth from place to place. The depth to this hardpan ranges from 19 to 48 inches on W-I, with an average of 37 inches from 14 determinations. On W-II, it varies from 8 to 36 inches below the surface, averaging 27 inches in 11 determinations. W-V has a range of 14 to 42 inches with an average of 25 inches in ten determinations. W-VI ranges from 9 to 48 inches to the hardpan, averaging 28 inches in 12 determinations, while W-VII varies from 5 to 33 inches with an average depth of 19 inches in eight determinations. However, the average depth to the soil horizon which most likely impedes the downward movement of water is somewhat less, in some cases, than the depths shown above. Estimates based on field conditions show that on W-I, the average depth to the impeding layer is 27 inches and on W-II, it is 26 inches. The average depth to mottling or to the horizon which shows definite effects from the drainage condition below it, is 19 inches for W-I and 22 inches for W-II. If the Hyattsville and Berwyn soil-profiles are underlain by a hardpan, it is at a greater depth than 48 inches below the surface, this being the limit of exploration.

Normalcy of precipitation--The average annual precipitation for the five-year period 1940-44, was about 1.25 inches below the 35-year Weather Bureau normal of 40.35 inches for College Park, Maryland. The average monthly depths in comparison with normal are shown in Figure 4. An investigation of the actual rainfall-intensities for 10-, 30-, and 60-minute durations was made and compared to YARNELL'S values, which were increased by ten, seven, and five per cent, respectively [3], because of the fact that his intensities were determined from uniform five-minute intervals as published by the Weather Bureau, whereas our actual intensities were the maximum values for the selected durations. All excessive rates of rainfall as defined by the Weather Bureau were used, or all above 1.80, 1.00, and 0.80 inches per hour for the 10-, 30-, and 60-minute intervals. The plotting was made on logarithmic probability paper for Precipitation-station R-1 for the whole period and also for the initial comparative period and the second period after change in practices.

Comparisons of our data with YARNELL'S modified values are shown in Figure 5. For ten-minute durations the 5.67-year period was about normal, the initial period of 3.2 years was slightly above normal, and the subsequent second period of 2.5 years fell somewhat below normal. For the 30- and 60-minute durations, however, all periods were subnormal. Since the periods of rise

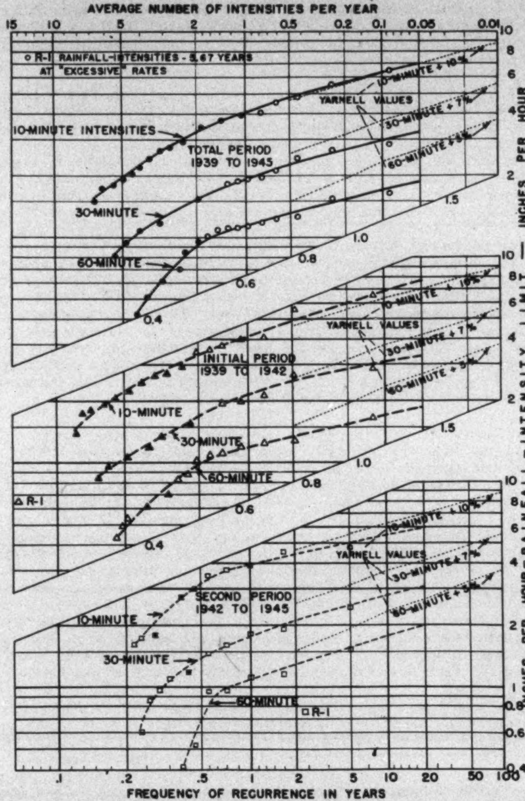


Fig. 5--Frequency of rainfall-intensities for total, initial, and second periods compared to modified YARNELL values

of the hydrographs for the five areas generally vary from six to 15 minutes, it appears that the ten-minute duration is best for judging the normalcy of the rainfall-events, although it is conceded that the magnitude of many of the peak-rates of runoff so far experienced might be somewhat lower due to the subnormalcy of the longer durations. It has been assumed, however, that the rainfall-intensities occurring during the periods were fairly normal and are reasonably representative of longer-term records.

Peak-rates of flow--On Figures 6 and 7 are shown four typical hydrographs of each of the five areas plotted to the same scale for easy comparison. Figure 6 shows hydrographs for the initial comparative periods and Figure 7 shows them for the period after changes in land-use were made. Reference to the hydrographs for August 19, 1941 (Fig. 6), and June 17, 1943 (Fig. 7), shows that it would be very difficult to try to evaluate them in terms of the rainfall-intensities and amounts, due to the evident complicated rainfall-patterns. For this reason a method of analyzing the frequency of recurrence of various peak-rates, by considering only the runoff-rates themselves, is presented.

Peaks above a selected minimum value--Since the areas under consideration flow only intermittently, a full duration-curve which would show the proportion of time that given limits of flow are exceeded could not be determined for them. By using peak-rates above selected minimum values and considering all values above this minimum, the average number of times per annum that peaks above a certain limit are equalled or exceeded, can be computed by the formula (1).

$$P = (2m - g)/2n \qquad (1)$$

P is the plotting-position, m is the number of terms from the top after peaks have been arranged in order of magnitude (for groups, the number of the smallest peak), g is the number of peaks in the group (unity for the larger single peaks), n is the number of years represented by the data [1]. In the case of groups, the average value of the peaks is plotted against the computed plotting-position. The underlying assumptions are that the data for the period being studied are a fair sample of a succession of such periods and that the maximum peak in the period of record is the median of the maximum peaks of a succession of like periods. In other words, the maximum peak, on the average, will be equalled or exceeded once in a period that is twice as great as that in which it occurred.

Comparison of longer with shorter periods under the same land-use--From the diagrams of cropping-procedures (Figs. 2 and 3) it should be noted that three of the areas remained in the same practice for the whole period of record, that is, W-I and W-V for 5.67 years and W-VI for 4.67 years. All peaks above 0.05 inch per hour were taken for W-I (76 peaks), and all those above 0.01 inch per hour for W-V and W-VI (49 and 109 peaks, respectively). These were computed by the method described above and plotted on logarithmic probability paper in Figure 8. Smooth curves were drawn through or among points by approximation. The two shorter periods for each area corresponding to the change in practice for paired watersheds were also computed and points plotted on Figures 9 and 10. The curves representing the data for these shorter periods are also

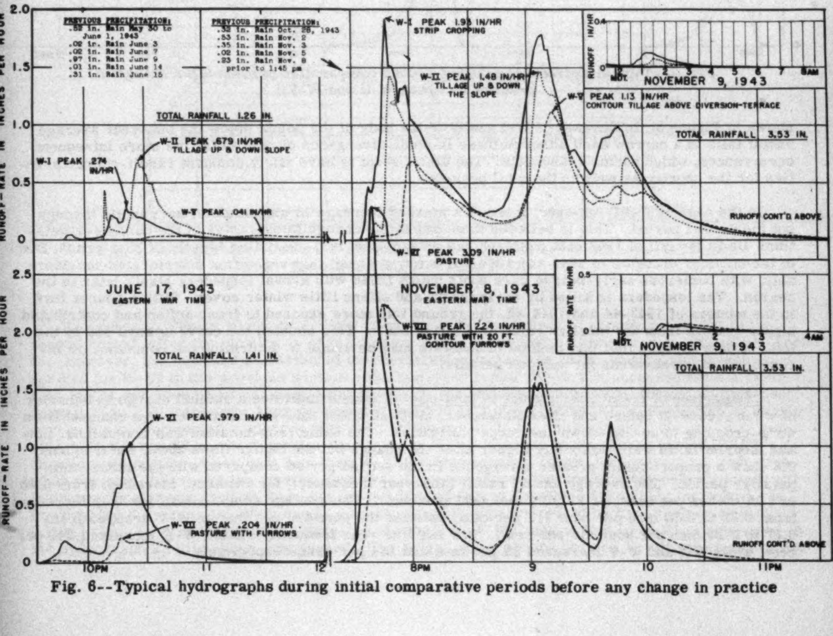


Fig. 6--Typical hydrographs during initial comparative periods before any change in practice

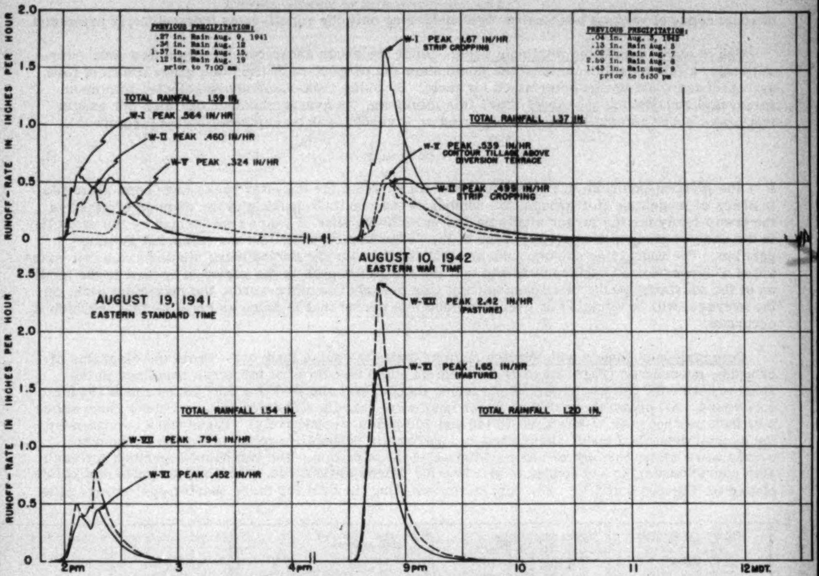


Fig. 7--Typical hydrographs during second comparative periods after change in practice on areas W-II and W-VII

shown in Figure 8. In the case of W-I and W-V the body of the points below the one-year average runoff falls in a narrow band although there is some divergence of curves for the more infrequent occurrences, which seems reasonable. The areas seem to have fairly constant runoff-characteristics for the shorter as well as the total periods.

In the case of W-VI, however, there is a marked increase in magnitude of the runoffs throughout the second period. This is believed to be due to the change in character of the pasture-vegetation. Up to the fall of 1942 both pastures had an excellent turf consisting largely of blue-grass. Due to the summer droughts of 1943 and 1944 and heavy grazing, this vegetation deteriorated considerably, with numerous early-season bare spots which filled with annual lespedeza plants later in the season. The lespedeza is killed by early frosts and offers little winter cover. With a poorer turf in the winters of 1943-44 and 1944-45, the ground was more exposed to frost-action and contributed higher runoffs from the smaller rains or melting snow. This boosted the curve upward and to the left. It thus appears that this method of analysis may be useful to determine the constancy or inconstancy of check-areas for various periods.

Comparison of areas after change in land-use--Figure 9 indicates a radical change in behavior of watershed W-II before and after November, 1942, at which time the cultivation was changed from strip-cropping to up-and-down-the-slope cultivation. The same crop-rotation was maintained. Low and medium flows were uniformly higher after the change but the higher flows above the frequency 0.3 show a proportionally greater divergence in the second period compared with the initial comparative period. The average annual runoff (one-year frequency), for instance, increased from 0.46 to 1.15 inches per hour, or 2-1/2 times (250 per cent). The average annual runoff for W-I decreased from 0.68 to 0.60 inch per hour (12 per cent) between the periods, and that on W-V dropped from 0.27 to 0.23 inch per hour (15 per cent). For the five-year frequency runoff, W-II increased 240 per cent, while W-I and W-V increased 29 per cent and 114 per cent, respectively.

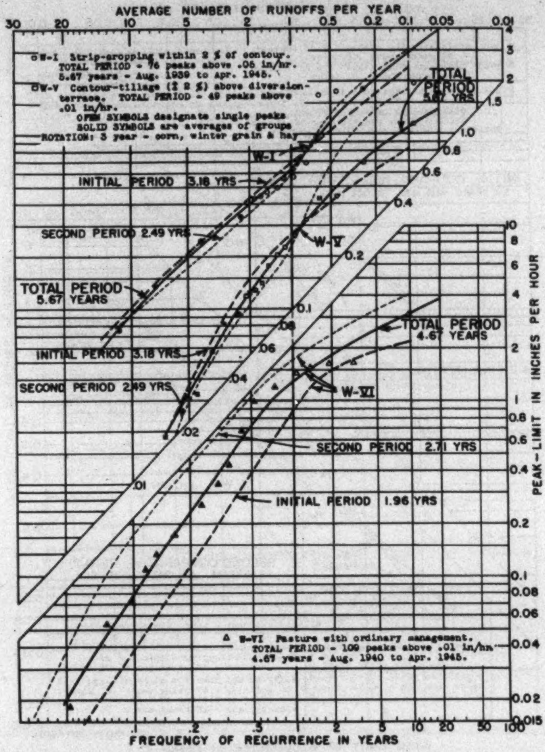


Fig. 8--Comparison of shorter periods with total period under the same land-use for areas W-I, W-V, and W-VI

Reference to Figure 10 shows a slight increase in the magnitude of runoffs for W-VII in the second period, after the plowing-in of the contour pasture-furrows, as compared to the initial period. However, the increase is attributed to deterioration in pasture cover-conditions already described for W-VI in the previous section. The one-year runoff for W-VII increased from 1.17 to 1.37 inches per hour or 17 per cent, whereas W-VI, the uncontrolled pasture, showed an increase from 0.87 to 1.70 inches per hour between the periods or a one-year runoff value greater by 96 per cent in the second period compared with the initial period. In the initial period, the one-year runoff for W-VII was 36 per cent greater than that for W-VI, whereas in the second period, W-VII showed a magnitude 19 per cent less than W-VI for the one-year runoff, an apparent net reduction of 55 per cent in favor of the contour-furrows. It was observed that the furrows held all the runoff from small rains and melting snow but, as the magnitude and duration of the rains increased, the furrows had a decreasing effect on the amount of runoff, as exemplified by the storm on November 8, 1943 (Fig. 7). A decrease in the time-lag of runoff on W-VII, behind that of W-VI is also noted in the hydrograph as this storm progressed. The height of the second peak on W-VII, which is greater

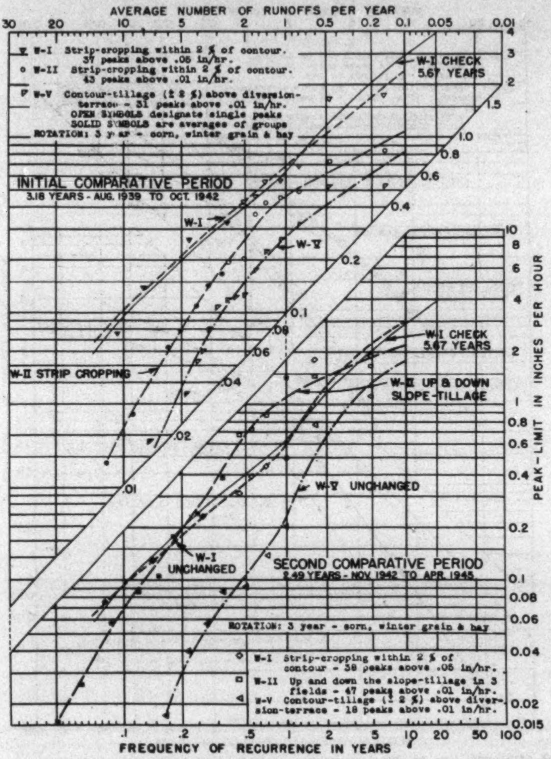


Fig. 9--Runoff-behavior of area W-II before and after change to up-and-down-the-slope tillage, compared to check-areas W-I and W-V

than that on W-VI, may be ascribed either to the difference in the rainfall-pattern on the two areas, or the partial failure of some of the furrow-ridges which may have changed the drainage-characteristics of W-VII.

Seasonal distribution of runoffs--It is possible to use the method to determine the seasonal frequency of runoffs by taking out the peaks for any desired season from consecutive years and handling them as if they were complete years. Figure 11 shows the distribution of runoffs on W-I and W-VI by the following seasons: full summers, May to October; full winters, November to April; early summers, May to July; late summers, August to October; early winters, November and December; and late winters, January to April. The winters were split up into two and four-month periods because November and December are generally frost-free and do not have a great deal of precipitation in the form of sleet or snow. Furthermore, the hay-strips and fields generally are plowed in late December or early January.

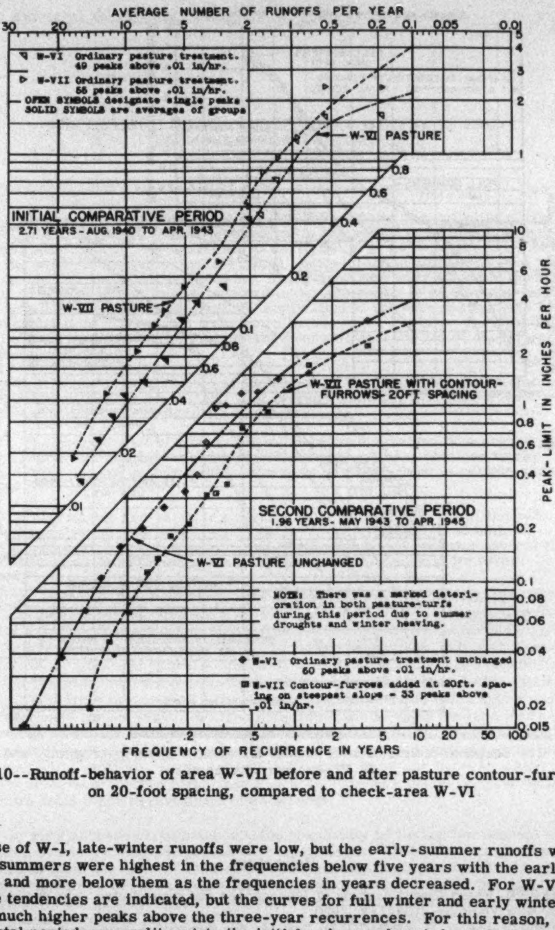


Fig. 10--Runoff-behavior of area W-VII before and after pasture contour-furrows on 20-foot spacing, compared to check-area W-VI

In the case of W-I, late-winter runoffs were low, but the early-summer runoffs were still lower. The late summers were highest in the frequencies below five years with the early winters diverging more and more below them as the frequencies in years decreased. For W-VI, more or less the same tendencies are indicated, but the curves for full winter and early winter for the total period show much higher peaks above the three-year recurrences. For this reason, the full winters for the total period were split up into the initial and second periods, and show very low runoffs for the initial period in contrast with the second period. The full-summer runoffs for the initial and second periods, plotted rather close together, but the second period was the higher of the two. (These two curves are not shown in Figure 11.) This seems to be rather conclusive proof of the deterioration of winter pasture-conditions in the second period as described heretofore and indicated in the curves in Figure 8.

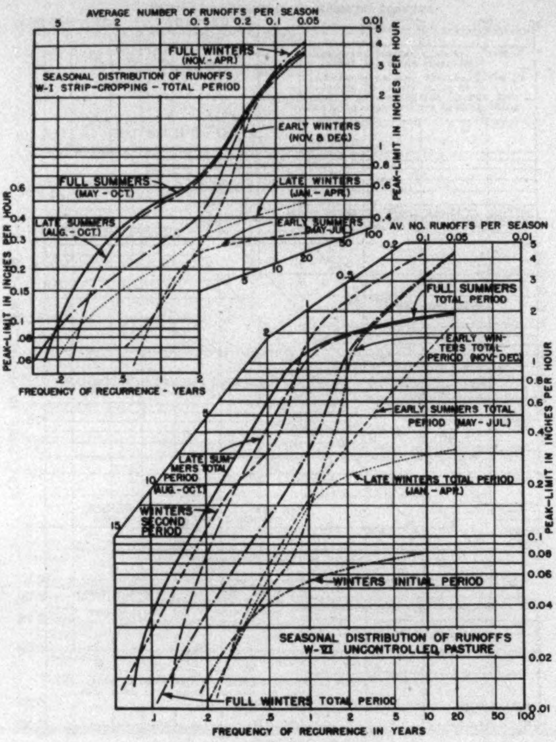


Fig. 11--Seasonal distribution of runoffs for area W-I, strip-cropping, and area W-VI, uncontrolled pasture

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THE RELIABILITY AND USEFULNESS OF THE ENERGY EQUATIONS FOR EVAPORATION

N. W. Cummings

Abstract--The derivation of the BOWEN equation for the ratio of convective and evaporative heat transports, is expressed in terms of modern turbulence-theory. All objections to the equation which have thus far come to the writer's attention are examined. Some of these objections turn out to be nothing but misapprehensions, while the others correspond to quantities of energy which, though indeterminate, are shown to be so small as not to require attention in the practical application of the energy equations to the problem of evaporation from a continuous water-surface. Incidentally, a rational method of using turbulence-theory without the aid of energy relations is suggested.

A mistake in computation in the report of the Bear Lake investigation published in 1940 is corrected. The average seasonal loss for the lake is reduced from 0.58 cm/day to 0.48 cm/day.

The energy point of view is shown to be characterized by a degree of directness and simplicity which has thus far never been obtained in any other way, except by calculation from gage heights, which is seldom possible.

Pan-records are valuable provided those characteristics of the pan are known which determine heat-leakage through the walls and bottom. There appears to be no experimental or observational evidence against the validity of the BOWEN equation. There is such evidence in its favor.

Introduction--Although many people have a feeling that the evaporation-rate from an open water-surface is determined by wind and humidity, this feeling is purely qualitative in nature, and great difficulty has always beset attempts to reduce it to any sort of useful quantitive form [see 1, 2, and 3 of "References" at end of paper]. It is reasonably possible that with respect to this, as well as to many other matters, postwar conditions will demand a far more scientific attitude than has prevailed in the past, but this does not necessarily require the qualitative intuitions to be abandoned entirely. It merely means that if they are used, they must be fitted into a carefully organized body of knowledge. In recent years, efforts have been made to apply modern ideas in turbulence-theory [4, 5, 6, 7]. What the outcome of this turbulence-attack on the practical problem of evaporation from lakes will be is difficult to forecast, but a solution based entirely on turbulence-theory and meeting economic demands, is not yet in sight. Apart from any success which such a theory may eventually achieve in its own right, items in it may serve a useful purpose by supplementing principles drawn from other departments of knowledge.

Energy--In view of these circumstances, the possibility of finding the correct answer through the conservation of energy, should receive careful attention. This principle places us in a strong position as judged from the point of view of directness and simplicity, because the basic measurement is, as will appear in the paragraphs following equation (10), exactly the same in kind as the quantity sought, and not greatly different in magnitude. In this respect it is excelled by nothing except a direct calculation from gage-heights, which is seldom possible. Of course, in the application, we must take account of every component of energy that cannot be proved negligible. One of these, which for a time seemed likely to be troublesome, is the heat transferred by convection between the water and the air, and it may, of course, go either way, depending on relative temperatures.

The manner in which this difficulty has been overcome provides a good illustration of the many useful forms which have been assumed by that far-reaching organization and simplification of knowledge, which is the true spirit of physics. The solution of the problem makes use of a quantity commonly denoted by R, and sometimes known as the BOWEN ratio, although other writers had used it before the beginning of BOWEN'S interest. As will presently appear, however, BOWEN made a brilliant and important contribution in connection with it. Spray will be regarded as presenting a separate problem. We may define R as the ratio of the convective component or "sensible heat," to the evaporation component or "latent heat." Its use may be illustrated by the following numerical example.

Merely for the sake of illustration, let us assume that (1) all components except latent and sensible heat can be disregarded; (2) for a certain hour, R is somehow found to be +0.10; (3) the sum of the two components for this same hour is 44 cal per sq cm. Then we know that $E + 0.10E = E(1 + 0.10) = 44$ cal/sq cm, making $E = 40$ cal/sq cm.

In other words, 40 cal of latent, and 4 cal of sensible heat, leave each sq cm during this hour. Dividing 40 cal/sq cm by the magnitude of the heat of vaporization, which can be taken as 5.8×10^2 cal/gram at ordinary temperature, gives 6.8×10^{-2} grams per sq cm for the hour.

The procedure is therefore straight forward, provided we have sufficiently accurate and reliable means of finding the magnitude of R. For this purpose BOWEN [8] derived the equation

$$R = J\,(T_w - T_a)/(P_w - P_a) \cdot P/760 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and showed that J must fall between 0.50 and 0.44 when the temperatures are in centigrade and pressures in mm of mercury. The dimensions of J are such as to make R a pure number. The temperature of the air is denoted by T_a and that of the water by T_w, while the partial pressure of the moisture in the air is P_a and the pressure of saturated vapor at the temperature of the water-surface, P_w. The barometric pressure is denoted by P. The range of variation of J is not serious because of the distribution of R with respect to evaporation. Whenever R is numerically large, the evaporation-rate tends to be small, so that the total indefiniteness is small.

This is shown quantitatively by the investigation conducted at Bear Lake in Utah and Idaho during the summer of 1937 [9]. Readings were made every two hours from 4^h to 20^h and at midnight, and R for pan and lake was computed for each individual observation throughout July, August, and September. The pan-evaporations for each month were then grouped according to the magnitudes of the accompanying pan R's, in class intervals of 0.10.

With 0.47 as an arbitrary value of J midway between the extreme limits of 0.50 and 0.44, R/J was computed for each R-interval, and the result multiplied first by 0.03, which is half the range of J, and then by the total evaporation falling within the R-interval, throughout the entire month. The sums of the partial products so obtained, gave an upper limit for the total indefiniteness for the month. The result turned out to be less than two per cent of the evaporation for each of the months. More will be said on the point in connection with equation (13).

A little later in this paper, BOWEN'S conclusion will be examined rigorously from the standpoint of turbulence-theory, but for the present we may inspect it in a more general way.

It will be observed that $T_w - T_a$ is of the nature of a driving tendency for sensible heat, and $P_w - P_a$ is a similar driving tendency for latent heat. All we are saying in equation (1) is, then, that the ratio of the transports is proportional to the ratio of the driving tendencies, and, although the proportionality-factor depends on the condition of the air with respect to turbulent or laminar motion, it nevertheless falls between the specified limits.

The first part of this statement seems intuitively obvious and has been verified by experiment, but the second part, the magnitude of J, may require examination. We can conduct the examination more easily, however, if we express the driving tendencies in terms of energy-concentrations instead of temperatures or pressures. For this purpose, as well as for the quantitative treatment which will come later, we shall adopt a notation in which θ is the energy per unit volume in the form of latent heat, y is the distance from the windward side of the lake measured parallel to the direction of the wind, f(x) is the wind velocity, while x is the distance above the surface, and D_L the diffusivity, either turbulent or molecular, for water vapor into air. Likewise, ϕ is the specific or sensible heat-density and D_S the diffusion-coefficient, turbulent or molecular, of heat-energy. The boundary conditions are that $\theta = \theta_0$ and $\phi = \phi_0$, at $x = 0$, and $\theta = \theta_1$ and $\phi = \phi_1$ along the line $x = x_1$ and $y = y_1$, close to the water surface. At any height, x_2, convenient for measurement, $\theta = \theta_2$ and $\phi = \phi_2$. The space immediately above the water-surface can be regarded as saturated at the temperature of the surface. Previously, θ_1 and ϕ_1 have been used for θ_0 and ϕ_0. The latent heat per unit-area transported upward with the evaporated water in unit-time is represented by Q_L, and the corresponding sensible heat by Q_S. Dimensionally, f_L and f_S are 1/length, but they are more completely defined in the third paragraph after equation (2a).

If then we write

$$Q_L = D_L(\theta_2 - \theta_0)f_L \quad \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

we have, so far as vapor-pressure difference is concerned, the substance of an idea which for many decades has been universally accepted by persons interested in evaporation, and which has been embodied in a vast number of empirical and theoretical equations.

The advantage of the form of equation (2) consists in its enabling us to regard D_L as the diffusivity, either turbulent or molecular, and in so doing, bring to bear on this particular problem important material, both theoretical and experimental, drawn from other fields. Thus the corresponding equation for the transport of sensible heat is well known, even though it has received relatively little attention in connection with evaporation. It is

$$Q_S = D_S(\phi_2 - \phi_0)f_S \quad \ldots \ldots \ldots \ldots \ldots \ldots (2a)$$

There is abundant experimental justification for saying that if θ is the energy-density at any point in the field of lake-influence, then $Q_L = -D_L \ \partial\theta/\partial x$. This relation is implied by SVERDRUP [5, p. 62] and by THORNTHWAITE and HOLZMAN [7, eq. 32].

We should observe, however, that $\partial\theta/\partial x$ and $\partial\phi/\partial x$ are the derivatives or gradients, at any point in the entire field, and therefore vary from point to point. The upward transport of moisture is accordingly not uniform throughout the field, and the variation is in general, both vertical and horizontal.

Moreover, since a complete mapping of the field with respect to energy-densities or their gradients, is impracticable, we must draw such inference as we can from measurements taken at two or more points, assuming a steady state, in order to avoid needless complexity. For this purpose we must recognize that at every point in the field, θ takes on such a value as is required for maintaining equilibrium between the net upward diffusive discharge of moisture into a small element of space surrounding the point, and the horizontal purging of this space by the wind. Thus when only two fixed points are used, $\partial\theta/\partial x$ at any point must be assumed equal to the difference in θ at the two selected points, multiplied by a quantity which depends on both the wind-conditions and the diffusion-conditions. This quantity is denoted by f_L. It depends also on the position of the variable point under consideration, and the fixed points at which θ is measured. The corresponding function for sensible heat is f_S. Thus D_L or D_S enters its respective equation in two ways, (1) directly as a coefficient, and (2) indirectly through f_L or f_S. (For justification of the steady-state assumption, see appendix.)

Of course, if more than two fixed points are used, a better evaluation of the expression for $\partial\theta/\partial x$ becomes experimentally possible. One or more of the fixed points may, but theoretically need not, be in the water surface. At least one should be in the air.

When the motion is turbulent all the way to the water surface, $f_L = f_S$ because, according to turbulence-theory, $D_L = D_S$ in that case [5, p. 63; 7, p. 21]. In still air, with conditions so controlled that $f(x) = 0$ for $x_2 \geqq x > 0$, $f_L = f_S = 1/x_2$.

For these two limiting cases, if we divide equation (2a) by (2) we obtain a result identical with equation (1) except for the change of units previously mentioned.

In practical applications, the units occurring in equation (1) are more convenient, but those employed in equations (2) and (2a) are better suited to the derivation. The conversion from one set to the other, with the corresponding change in the numerical magnitude of J, is discussed by BOWEN [8, p. 785] and by SVERDRUP [5, p. 63].

Now, if D_S and D_L represent turbulent diffusivities, their ratio, as previously pointed out, is unity, regardless of the magnitudes of the coefficients taken separately. On the other hand, if they are molecular diffusivities, their ratio is, according to experiment and molecular theory, very nearly 0.88 [8; 10, p. 421]. If, then, actual conditions are neither entirely turbulent nor entirely molecular, $1.00 > D_S/D_L > 0.88$.

We must still take care of the possibility that $f_S/f_L \neq 1$, which may occur if air near the water-surface is in laminar motion. For this purpose we may conveniently write $J_1 = (D_S/D_L)(f_S/f_L)$.

We can then say at once on physical grounds that $1.00>J_1>0.88$, for the case of laminar flow must be intermediate between that of still air, and that of turbulent flow. This is evident from the fact that, leeward of the instruments, a concentration of each energy-component must build up, but that one must build up faster which has the greater diffusivitiy. Each of these concentrations must exercise a choking back effect, which must be greater for the greater concentration, that is, for the component having the greater diffusivity. Hence any motion, either turbulent or laminar, tends to make J_1 approach unity. On the other hand, it must be obvious that molecular transport never can make J_1 exceed unity. If $1.00>J_1>0.88$, then $0.50>J>0.44$, as can readily be seen by equating the J_1 and J expressions for R, and then simplifying.

By thus dividing the equations for the two components, we gain two important advantages. The first is that we eliminate any serious trouble due to uncertainty in the magnitudes of f_L and D_L. The seriousness of the trouble encountered, when any direct use of equation (2) or any form of equation corresponding to it is attempted, may in part be judged from the uncertainty as to the magnitude of the diffusivity, for in turbulent motion it may be a thousand times or more greater than in true molecular transport. The multiplier f_L may not vary over such a wide range, but it should receive adequate attention when it is not made to cancel out. Quantities which at present are extremely difficult to measure accurately, enter the functions f_L and D_L in such important ways as to aggravate the unreliability of computations based entirely on turbulence-theory [5, p. 119; 7, eq. 36; 7, p. 29].

The second advantage gained from the ratio R, is concerned with the precision of measuring the energy-concentrations. As the foregoing illustrative example shows, we divide the available energy by $(1+R)$. Now, the error in R can be a large percentage of R itself, and still be negligible by comparison with $(1+R)$. The significance of this lies partly in a possible wide variation of simultaneous temperatures taken at different points on a lake-surface [11, Table 2]. Although different observers are not in perfect agreement, the percentage variation of $(P_w - P_a)$ for a given lake at a given time, may in some cases be comparable to the percentage variation of evaporation for different lakes. Consequently, turbulence-theory or any other idea that makes the computed evaporation proportional to $(P_w - P_a)$, or to any quantity which varies in a corresponding manner, may suffer by comparison with the conservation of energy. If so, the disparity is all the greater because of the relative insensitiveness of R to change in water-temperature when the air is cooler than the water, which is always the case at times of maximum evaporation-rate [5, p. 64]. This possibility applies especially to a lake so shallow as to make the water-surface temperature exceed the air-temperature in the datyime, when the horizontal gradients are large.

For a deep lake, the difficulty takes a somewhat different form. In that case the greatest evaporation rate is likely to occur at night or in early morning, when the horizontal gradients are small. But the observations for determining vapor-pressure difference must be made with this fact in mind. As a rule this has not been done, and therefore great care must be exercised in using data that have been obtained in the past.

If P_w is replaced by the vapor-pressure at a second atmospheric point, then additional trouble is introduced by the extremely small magnitude of the resulting vapor-pressure difference.

The disappointing results obtained by ROHWER at Fort Collins [3] may be due in part to the irregular variations of surface-temperature at any given time. His investigation was a remarkably fair test of the entire empirical equation-idea. Although the work was done with great care and thoroughness, the average error was 29.7 per cent [3, Table 16], which is a substantial fraction of the percentage-variation over the entire continental United States. The work of other investigators, and the possibility of future projects of this kind should, however, be carefully considered [2].

The foregoing elementary considerations lead us to the conclusion that J never can fall outside of the limits specified by BOWEN, and suggest that we must dismiss as unfounded the following objection to his equation by HOLZMAN [12, p. 658].

"In his derivation of the equation for R, BOWEN assumed laminar flow throughout. The coefficients of vapor-diffusion and heat-conduction were employed in setting up the heat-transfer equations. Consequently, the observations of P_a and T_a are restricted to the laminar layer. Since the laminar boundary-layer has a variable thickness, frequently of the order of one mm or less, it is impracticable to make the necessary observations in order to determine R. When measurements of P_a and T_a are made they are almost invariably representative of the turbulent atmosphere and when substituted in BOWEN'S equation a value for R will be obtained that will have no theoretical validity."

And later:

"CUMMINGS has recognized the trouble involved in determining the convective component, K, in the heat-balance equation, but has assumed that the BOWEN ratio conveniently eliminates the difficulty in determining this quantity. It would seem that until a more rigorous method for determining the heat-exchanges due to convection is applied, the evaporation from a body of water as computed from the heat-balance equation may be considerably in error."

The objection clearly reveals a misapprehension, due in some degree, perhaps, to the fact that BOWEN may not have explicitly emphasized turbulent flow as such. There is, however, not the slightest doubt that his theory does take care of it implicitly, by the use of inequalities and verbal explanations. BOWEN'S wording was a natural and logical one in view of the limited extent to which turbulence-theory had been developed at the time he wrote. The author of the objection gives us no clue as to the direction of the supposed error. Does he believe that when the instruments are in the turbulence-region, the calculated R is too large or too small?

Moreover, the objection accompanies a recommendation of a procedure that makes the calculated evaporation proportional to a small vapor-pressure difference [7, eq. 36] and fails to take proper account of f_L. It integrates an equation [7, eq. 34] as if the moisture-transport were independent of height, and uses the result as if the transport were independent of horizontal position. In other words, it amounts to writing zero for the left member of equation (3) in the quantitative treatment, although there is no physical reason for expecting either $\partial\theta/\partial y$ or $f(x)$ to vanish generally.

Quantitative treatment--By consideration of the equation of continuity in connection with the fundamental equation of heat conduction, BOWEN establishes two differential equations which determine the distribution of the two energy-components involved in the ratio R [see also 10, eq.157, for a similar equation by SUTTON]. In the notation already given, which is a slight modification of BOWEN'S, these equations are:

$$(\partial\theta/\partial y)f(x) = \partial\left\{D_L\ \partial\theta/\partial x\right\}/\partial x \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$(\partial\phi/\partial y)f(x) = \partial\left\{D_S\ \partial\phi/x\right\}/\partial x \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3a)$$

For the special case in which $f(x) = Kx^n$, EPSTEIN [8] has obtained a solution, treating D_L and D_S as constants. The equations could have been solved without this latter limitation, but it is not necessary for our present purpose. As here used, K has a meaning different than in the HOLZMAN quotation. (See end of paragraph following equation (9) for further remarks on the use of K.)

We may conclude at once, from boundary conditions and dimensional considerations, that the general solution must be reducible to the forms

$$(\theta - \theta_0) = (\theta_2 - \theta_0)\, F_L(x, y, D_L, \text{wind parameters}, x_2, y_1) \ldots\ldots \quad (4)$$

and

$$(\phi - \phi_0) = (\phi_2 - \phi_0)\, F_S(x, y, D_S, \text{wind parameters}, x_2, y_1) \ldots\ldots \quad (4a)$$

in which the functions F_L and F_S are dimensionless multipliers which become zero when $x = 0$ and $y = y_1$, and unity when $x = x_2$ and $y = y_1$. We can safely choose y_1 as small as $\{f(1\text{cm})\text{cm/sec}\}\{1.2\text{ sec}\}$ and probably smaller (see appendix).

If we now multiply the derivative of (4) by D_L, and of (4a) by D_S, and divide, we obtain, since $F'_S = f_S$ and $F'_L = f_L$

$$R = (D_S\ \partial\phi/\partial x)/(D_L(\partial\theta/\partial x) = [D_S(\phi_2 - \phi_0)/D_L(\theta_2 - \theta_0)][F'_S/F'_L] = J_1(\phi_2 = \phi_0)/(\theta_2 - \theta_0)$$

As previously indicated, when the motion is entirely turbulent from the water-surface to the plane $x = x_2$, $J_1 = 1$, and the upper limit of J in equation (1) is 0.50. It is obvious from physical considerations that if the motion is not purely turbulent, that is, if there is some truly molecular diffusion, J_1 must be somewhat less than unity if it changes at all, because we cannot, by introducing molecular diffusion, cause the smaller molecular coefficient to yield the greater transport. Hence $J_1 \leqq 1$, in all cases.

If the transport ever could be entirely molecular all the way up to the plane $x = x_2$, we could, as will presently be shown, say that $J_1 \geqq 0.88$, but it is found by observation that the molecular layer over a lake is never more than a few millimeters thick. We must accordingly deal with the case in two steps.

First assume temporarily, that we can measure the energy concentrations in the plane $x = x_i$ and that this plane is in the molecular layer. In this case, since the diffusivities are constant, the EPSTEIN solution applies with such modifications as are required by the other changes, and we may proceed as follows:

$$\text{Let } G_L = [K/(n+2)^2 D_L y]^{1/n+2}$$

While G_{1L} is the same function with y_1 replacing y; also G_S and G_{1S} have corresponding meanings; then

$$\theta = \theta_0 + (\theta_i - \theta_0) \int_0^{G_L x} e^{-\sigma^{(n+2)}} \, d\sigma \Big/ \int_0^{G_{1L} x_i} e^{-\sigma^{(n+2)}} \, d\sigma \quad \ldots\ldots\ldots\ldots \quad (5)$$

and we have a corresponding solution for (3a), which we may call equation (5a).

Now, the diffusion from unit-area of water-surface, or more strictly the diffusion across the plane $x = \underline{a}$, when $\underline{a}$ approaches zero, is

$$Q_L = -D_L \ \partial\theta/\partial x = D_L (\theta_i - \theta_0) G_L / N_L \quad \ldots\ldots\ldots\ldots \quad (6)$$

Likewise

$$Q_S = -D_S \ \partial\phi/\partial x = D_S (\phi_i - \phi_0) G_S / N_S \quad \ldots\ldots\ldots\ldots \quad (6a)$$

Where

$$N_L = \int_0^{G_{1L} x_i} e^{-\sigma^{(n+2)}} \, d\sigma, \text{ and } N_S = \int_0^{G_{1S} x_i} e^{-\sigma^{(n+2)}} \, d\sigma \quad \ldots\ldots\ldots \quad (7)$$

Division gives

$$R = (D_S/D_L)^{(n+1)/(n+2)} (N_L/N_S)(\phi_i - \phi_0)/(\theta_i - \theta_0) \quad \ldots\ldots\ldots\ldots \quad (8)$$

As BOWEN points out, n cannot be negative, and it will be observed that

$$(D_S/D_L)^{(n+1)/(n+2)} (N_L/N_S) = J_1$$

and is never less than 0.88 nor greater than unity so long as we are dealing with the molecular layer. We may now generalize to a layer of any thickness.

First, consider the sharpest possible transition from molecular to turbulent conditions as we ascend from the water-surface. Also regard the turbulence-coefficients as very large in comparison to the molecular ones. As we carry these combined concepts further and further, we approach more and more closely a condition in which the readings of our atmospheric instruments must be independent of their height so long as they are in the turbulent layer and not out of range of the lake-influence. For such heights they give us the conditions at the top of the molecular layer, so that the expression for J_1 holds even though the energy-concentrations are measured far above the level for which it was originally derived.

Now as we recede from this extreme condition, a concentration of each energy-component builds up in the lower part of the turbulent layer, or in the transition-layer, but that concentration builds up in greater amount which corresponds to the greater diffusivity. The flux of each component is accordingly retarded, but the retardation is greater for the latent heat. In order, then, to make our computed R agree with the true R, we must make $J_1 > 0.88$.

Hence, whether the surface is rough or smooth, that is, whether turbulence extends all the way down to the water-surface or not, we may always say that $1.00 \geqq J_1 \geqq 0.88$, for all levels with which we are concerned.

By way of illustration, it may be interesting to deal especially with a particular case of turbulent motion which has received a great deal of attention. We may first note that the product of the turbulence-diffusivity and the wind-gradient is ordinarily assumed constant near the surface [5, p. 119; 7, p. 20; 10, p. 248].

According to common and apparently well-founded assumptions in turbulence-theory, when the surface is rough, the turbulence-diffusivity is proportional to $(x + x_0)$ and the wind to $\ln (x + x_0)/x_0$ [5, p. 119].

It is, however, highly unlikely that available data can discriminate between these functions and two others which can conveniently be used in their stead. These are $(x^2 + x_0^2)^{1/2}$ for the turbulence-diffusivity together with $\log_e (x + \sqrt{x^2 + x_0^2})/x_0$ for the wind. Then so long as x and x_1 are small in proportion to x_0, which is of the order of 1 cm [5, p. 120; 10, p.248], $D_S = D_L$ may be regarded as constant, and $f(x)$ as proportional to x, so that the EPSTEIN solution applies.

We thus have a simple basis for applying turbulence-theory without the aid of energy-relations, which will become directly applicable as soon as we are provided with a satisfactory method of finding those constants which determine wind-and vapor-pressure relations, and which we must know in order to apply that theory in any way that has thus far been proposed.

We are now in a position to deal with objections recently raised by HICKOX [13, p. 1318]. Although this writer is to be commended for his remarks about insulation of the pan, the following passage in his paper seems unable to endure careful examination.

> "In all cases the heat lost by convection has been an uncertain quantity. It was assumed by MR. SCHMIDT that there was a ratio between the heat lost by convection and that used in evaporation since the processes of heat transfer by convection are analogous. I. S. BOWEN made the same assumption later and wrote at length to substantiate it, although in the meantime MR. ANGSTROM had shown the impossibility of such a ratio, pointing out that if it existed, there would be, for a temperature gradient of zero, either no convection and no evaporation, or convection and a corresponding evaporation. It is obvious that both conditions are absurd. The first condition might be satisfied if the atmosphere were saturated with water-vapor, but the second condition is impossible. Furthermore, MR. BOWEN assumed equilibrium-conditions which seldom exist. Water-temperatures are constantly rising and falling, so that the storage of heat is a considerable item in the energy balance, at times amounting to many times the energy used for evaporation. Under these conditions, the ratio varies considerably and in fact loses its significance entirely. MR. BOWEN'S ratio can be significant only if applied to average conditions over a period of time long enough so that storage of heat is not a factor."

The second and third sentences are bracketed together by the words "same assumption" and are evidently intended to support the first. Actually they fail to do this, for the combined sentences constitute an inaccurate assertion. The thing ANGSTROM (Geografiska Annaler, 1920) denies, is not the existence of the ratio R, but its approximate constancy. The BOWEN equation, being free from any such assumption of a constant R, is not subject to the ANGSTROM objection.

Apart from this breakdown of its support, the initial sentence is contrary to fact on its own account. This is made obvious by the use of the words "in all cases" because in a very important case, $R = 0$, there is no uncertainty. Moreover, when $R = -1$, the equation is in accord with the well known wet and dry bulb-formula. In view of the simple form of the equation, these two cases would suggest its validity over a wide range, even if no other evidence in its favor were available.

Is the expression "equilibrium-conditions" to be taken as synonymous with steady state? If so, HICKOX is criticizing JEFFRYS and SUTTON, as well as BOWEN [10, pp. 270-275]. The objection is idle because it gives no indication as to the magnitude of the departure from actual conditions (see appendix). Furthermore, what has heat storage to do with the relation of the steady state to R? Heat storage depends on the average volume-temperature, while R depends on the surface-temperature. The last two sentences are obviously unfounded.

Radiative diffusivity--A question has been raised regarding the relation between the thermal conduction involved in R, and a somewhat similar process associated with back radiation. The water-vapor over a lake is transparent to some of the wave lengths contained in the back radiation from the lake, but rather highly opaque to others. A substantial part of the total radiated energy is probably absorbed, therefore, within a short distance above the water-surface. In the steady state any particular layer must discharge and receive energy at equal rates, and one way of discharging is by re-radiation, which, of course, must take place both upward and downward. Its rate must depend on the temperature of the layer. There is thus a complex interaction among the various radiating layers, as well as between all of them and the lake. BRUNT [10] has applied careful analysis to a problem which involves this interaction among the various radiating layers, and found that, under the conditions which he was considering, the whole thing is mathematically analogous to heat-conduction, and the rate at which this part of the radiant energy gets away from the Earth's surface, is proportional to the temperature-gradient. The proportionality factor, with dimensions properly adjusted, is called the radiative diffusivity. BRUNT is very careful, however, to point out the tremendous difficulties encountered in the analysis, and the various assumptions which must be made. Some of these assumptions may under some conditions be far from the truth. He suggests the term "w-radiation" to designate the energy involved in this complicated process. The symbol R_w will designate the ratio of this energy-component to the latent heat, and a method of dealing with it will be described presently.

Fundamental energy equation--Coming back to the thermodynamic relations, we have as the basic equation for the evaporation occurring during any given time interval,

$$E = (I - B - S - LER - C)/L \quad \text{(9)}$$

where E is the evaporation expressed in centimeters of depth, I is the incoming radiation per square centimeter of surface, B the total back radiation, that is, the low temperature radiation from the water-surface plus reflected radiation, and S the heat consumed in warming the water. As already indicated, LER is the correction for heat received from the air or given up to the air as sensible heat, while C is a combined correction for heat-leakage through the walls of the container, expansion of the water, and, in the case of a lake, for heat carried by flowing water. It is supposed that all the quantities in the numerator are expressed in gram-calories per square centimeter of open water-surface, and are to be integrated over the same time interval as E. It may at first not be obvious that S and C can be thus expressed, but if the total amount of heat stored in a lake or entering by the methods to which C refers, be divided by the lake-surface area, then a definite part of each of these total quantities of heat will be allocated to a column under each square centimeter. By thus centering attention on a column of water having a square centimeter cross-sectional area, and a depth equal to the average depth of the lake, we make all the quantities in the numerator comparable, and can express them in the same units. The heat of vaporization in gram-calories per cubic centimeter is denoted by L [1, 9, 14, 15]. In some earlier papers, K has been used for LER.

It is convenient to replace I - B by H, so that the equation can be written

$$E = (H - S - C)/L(1 + R) \quad \text{(10)}$$

Since this equation is based on well established principles of thermodynamics, it applies to all water-surfaces however large or small, and to all conditions of wind, humidity, and air-temperature, subject to the indeterminate case which arises when $H - S - C = 0$ and $R = -1$. This case seems interesting as a basis for a derivation of the well known wet and dry bulb formula, which is free from objectionable assumptions contained in some other derivations. The case is, however, not important from the standpoint of evaporation from lakes because, as previously pointed out, the evaporation is small when R is negative.

If then, a thermally insulated pan is placed near a large water-surface, the equation will apply to the pan with one set of measurements and to the lake with a somewhat different set. The two sets of measurements are not entirely independent. Thus I is the same for both, if the air-masses above are alike in temperature and water-content; and experience seems to show that the same wet- and dry-bulb temperatures will serve for both the pan R and the lake R. This is because variations in θ, which, on account of the small gradients at the level x_2, might increase $\partial\theta/\partial x$ by 100 per cent or more at that level, are quite negligible in comparison with $(\theta_2 - \theta_0)$, the magnitude of which is determined chiefly by conditions very close to the water-surface. In general, however, S and θ_1, or θ_0 will need to be determined independently for the two bodies of water. The pan-evaporation can easily be measured directly. The frequency of these measurements must be properly adjusted to the daily cycle.

Obviously, the pan offers no difficulty in determining S, but for the lake the procedure would be expensive for short time-intervals. In practical work, this is not likely to be a drawback as judged from the standpoint of our interest in the lake, for seldom if ever is a knowledge of evaporation for short time-intervals needed. We must, however, find a suitable $\bar{R}$ or average R for the lake, defined by the relation

$$\Sigma\left\{LE(1 + R)\right\} = (1 + \bar{R})\Sigma\left\{LE\right\} \quad \text{(11)}$$

In the Bear Lake paper [9] a certain procedure is outlined for accomplishing this, but in the process of testing an alternative procedure, the writer recently discovered a mistake in the original computation. As a result, the curves mentioned in the notes on page 520, but not shown in the paper, should be disregarded, and the tables should be amended.

The alternative procedure is as follows: The greatest lake R occurring during any elementary period throughout the daily cycle is greater than the true lake $\overline{R}$. $\overline{R}$ for the pan appears to be less than $\overline{R}$ for the lake, because during July only six per cent of the total evaporation from the pan at Bear Lake occurred while R was negative; for August the percentage was 16; and for September, 22; and whenever R of the lake is positive, it tends to be greater than R of the pan. Also, many experiments tend to show that the evaporation-rate increases as the surface-area decreases, suggesting an increase in $\overline{R}$ with increase in area [13, p. 1312; see also 8, eq. 12; 10, pp. 274-275].

If then, we set the lake $\overline{R}$ equal to the arithmetic mean of the pan $\overline{R}$ and the greatest lake R, our error will, so far as this matter is concerned, be half the spread between the minimum and maximum so chosen. Moreover, this is the main source of error in the entire computation, and although there does not appear to be any other evaporation-estimate for a large deep lake, which is known to be subject to an error less than this, a reduction of the range of this particular source of indefiniteness in $\overline{R}$ is desirable.

It seems reasonable to suppose that such a reduction could be accomplished by making the pan larger, that is, making it a tank, say six feet deep and of comparable diameter, for such a tank would have a larger $\overline{R}$ than does the pan, notwithstanding the small difference observed at Pasadena early in the season [see 9, table 2, lines 9 and 10]. Moreover, these dimensions could very reasonably result in a tank-surface cooler than the lake-surface at all times, giving direct observational proof of a tank $\overline{R}$ less than the true lake $\overline{R}$.

Pending the possibility of procuring such a tank, we may use the relation

$$\overline{R} = \left\{JP/760\right\} \left\{\Sigma(F_1 \Delta t)/\ \Sigma(F_1 \Delta p)\right\} \text{ where } F_1 = E/\Delta p \quad \ldots\ldots\ldots\ldots \quad (12)$$

The Δt and Δp used in computing $\overline{R}$ refer to the lake, but the E and Δp for computing F_1 relate to the pan. This $\overline{R}$ probably is less than the true $\overline{R}$ because it neglects the excess of temperature of the lake over that of the pan at night and in early morning, when instability and therefore evaporation-rate appear to be greatest. It may be noted that over land, maximum stability occurs near the ground late at night, but the land differs from a lake, especially a deep one, in respect to the daily cycle of its temperature. The ground, air and pan, each in relation to its own average temperature, tend to be cooler than the lake at night and in the early morning, while the ground and air tend to be cooler than the pan. Table 1 shows this relation for air, pan, and lake, and we may safely infer that it holds for the ground also [5, p. 69].

As a check on the probability respecting equation (12) an attempt was made to find a definite relation between evaporation-rate and instability, that is, between loss from the pan and difference between water-surface temperature of the pan and air-temperature. Notwithstanding the unmistakable preponderance of evaporation-rate with positive algebraic sign of R, however, this new relation failed to develop. The most probable explanation appears to be found in a buckling of the material of the pan with change of temperature which, though cancelling to zero over a 24-hour interval, and thus not affecting the main computation, might mask the effect of instability. The remedy consists in making the new tank circular in section, and having a part of a spherical surface as the bottom. It should, moreover, be made of rather heavy material.

The revised computations are shown in Tables 1 and 2, which are corrections of Tables 2 and 3 in Reference [9].

For the lake, C is usually negligible, and for the pan it can be determined.

The energy component which in equation (9) was designated as B, can be regarded as consisting of two parts. One of these has been called the w-radiation and the other, to which the lower layers are transparent, may be denoted by b. Let $\Delta(LER_w)$ represent the difference between w-radiation of the pan and lake, and Δb the corresponding difference for the remaining radiation. Then the numerical data for the pan and lake, when substituted in equation (10), enable us to eliminate H, thus,

$$\left\{LE(1+R) + S\right\}_{lake} = \left\{LE(1+R) + S + C\right\}_{pan} + \Delta(LER_w) + \Delta b \quad \ldots\ldots\ldots \quad (13)$$

Table 1--Averages for Bear Lake, July to September, 1937

	Hour										Daily total or average
	4	6	8	10	12	14	16	18	20	24	
Month of July											
(1) Dry bulb, °C	12.5	13.2	17.5	21.3	23.7	25.4	25.7	23.3	18.9	14.9	
(2) Wet bulb, °C	10.9	11.3	14.5	16.8	17.9	19.4	19.0	17.8	15.7	13.0	
(3) Pan surf.,temp.°C	14.8	14.3	16.1	20.2	25.4	29.1	30.0	28.0	23.8	18.6	22.0
(4) Lake surf.,temp.°C	19.0	19.7	20.3	21.7	23.3	24.4	24.6	24.0	22.0	20.7	22.0
(5) R for pan	+0.23	+0.17	-0.24	-0.09	+0.05	+0.09	+0.10	+0.12	+0.18	+0.18	
(6) R for lake	+0.30	+0.29	+0.13	+0.02	-0.05	-0.13	-0.15	-0.16	+0.12	+0.23	
(7) Pan evap., cc	289	96.8	67.6	92.2	124	226	355	417	370	345	2382
(8) E, cm	.0777	.0261	.0182	.0248	.0334	.0608	.0955	.1123	.0995	.0926	0.64
(9) LE, cal/sq cm	45.0	15.1	10.6	14.4	19.4	35.3	55.5	65.2	57.7	53.8	372
(10) LE (1 + R)	54.0	18.1	10.9	12.7	18.6	37.8	60.6	71.6	65.2	63.5	413
(11) Pan evap., in											0.25
Month of August											
(1) Dry bulb, °C	10.5	9.7	15.1	20.3	24.3	26.6	26.4	24.4	18.6	14.3	
(2) Wet bulb, °C	8.4	7.6	11.3	14.2	16.8	18.0	18.3	17.7	13.2	10.4	
(3) Pan surf., temp.°C	13.1	11.8	12.8	17.2	23.0	27.3	28.2	26.6	22.9	17.6	20.0
(4) Lake surf.,temp.°C	20.8	20.3	20.5	21.6	22.9	23.9	24.3	24.1	23.2	22.3	22.4
(5) R for pan	+0.27	+0.24	-0.37	-0.32	-0.09	+0.01	+0.03	+0.05	+0.13	+0.16	
(6) R for lake	+0.35	+0.36	+0.21	+0.05	-0.10	-0.12	-0.09	-0.02	+0.15	+0.24	
(7) Pan evap., cc	306	140	64	74	141	250	386	491	358	415	2625
(8) E, cm	.0824	.0377	.0172	.0199	.0380	.0673	.1038	.1323	.0964	.1117	0.71
(9) LE, cal/sq cm	47.8	21.8	10.0	11.5	21.9	39.1	60.1	76.6	55.9	64.8	410
(10) LE (1 + R)	57.1	27.1	9.7	8.6	18.4	37.9	61.6	80.0	60.1	74.3	435
(11) Pan evap., in											0.28
Month of September											
(1) Dry bulb, °C	7.8	6.6	11.0	16.4	19.8	21.2	21.3	18.7	14.1	10.5	
(2) Wet bulb, °C	5.4	4.8	7.8	11.8	13.3	14.5	14.3	13.2	10.1	8.0	
(3) Pan surf.,temp.°C	10.3	8.8	9.3	13.9	17.9	21.9	22.7	20.9	17.8	13.6	15.7
(4) Lake surf.,temp.°C	17.4	16.8	17.1	17.9	19.8	20.4	20.2	19.6	19.1	18.3	18.7
(5) R for pan	0.22	0.24	-0.41	-0.29	-0.16	+0.02	+0.05	+0.10	+0.19	+0.21	
(6) R for lake	0.36	0.41	0.29	0.07	0.00	-0.04	-0.06	+0.05	0.22	0.32	
(7) Pan evap.,cc	187	112	74	59	97	178	310	280	172	226	1695
(8) E, cm	.0502	.0301	.0199	.0158	.0260	.0478	.0832	.0751	.0461	.0606	0.45
(9) LE, cal/sq cm	29.1	17.5	11.5	9.2	15.2	27.9	48.6	43.8	26.9	35.4	265
(10) LE (1 + R)	32.6	21.1	11.3	6.4	14.8	25.8	47.8	45.1	30.8	41.5	277
(11) Pan evap., in											0.18

Note: This table is a correction of Table 2--Averages for Bear Lake, July to September, 1937 in paper cited in Reference [9].

Lines (1) through (6) show the averages for the month, of instantaneous values at the given hour.

Lines (7), (8), and (9) show the averages for the month, of the evaporations occurring during the elementary time intervals ending at the times indicated.

Line (10) is the average for the month of the function $\{LE\ 1 + (R_1 + R_2)/2\}$, where R_1 and R_2 are the values of R for the pan at the beginning and end of an elementary time-interval indicated.

There were a few strongly negative R's, some less than -1.00, which influenced the average R's appreciably, but, on account of the accompanying small evaporations, had little or no effect on the averages of LE(1 + R). They had only a slight effect on the R's computed from average temperatures.

The area of the water-surface of the pan was 3716 sq cm.

Table 2--Steps in computation

	July	Aug	Sep	Seasonal average
(1) Body temp. of pan at beginning of monthly series	20.5	18.0	17.5	
(2) Body temp. of pan at end of monthly series	18.0	17.5	11	
(3) Heat storage of pan = S = 18 × av daily temp change	-1.6	-0.2	-3.4	
(4) Radiation as measured by pan = $H = S_{pan} + \Sigma\{LE(1+R)\}_{pan}$	411	435	274	
(5) $\Delta B = 0.5 \times 24 \times$ (Pan surf. temp. - Lake surf temp.)	00	-29	-36	
(6) Corrected radiation = H adjusted to lake	411	406	238	
(7) Av. daily warming = S_{lake}	227	-111	-65	
(8) $(1+\bar{R})\Sigma LE_{lake} = -S_{lake} + S_{pan} + \Sigma\{LE(1+R)\}_{pan} + \Sigma\Delta B$	184	517	303	
(9) Pan$(1+\bar{R}) = \Sigma\{LE(1+R)\}/\Sigma\{LE\}$ from Table 1	1.11	1.06	1.04	
(10) (1 + max lake R) from Table 1	1.30	1.36	1.41	
(11) $[\{1+\bar{R}\}_{pan} + \{1 + \max R\}_{lake}]/2$	1.20	1.21	1.23	
(12) $[(\Sigma\{F_1 \Delta t\})/(\Sigma\{F_1 \Delta p\})][\ ]P/760]$	.14	.16	.20	
(13) Assumed $(1+\bar{R})$ for lake	1.17	1.18	1.22	
(14) Lake evap., cal/sq cm (average daily) = (8)/(13)	157	438	248	281
(15) Lake evap., cm	0.272	0.754	0.429	0.483
(16) Lake evap., in	0.107	29.8	0.168	0.191
(17) Evap. from Weather Bureau pan, in	0.239	0.254	0.169	0.221
(18) Ratio: Lake/W.B. pan	0.45	1.17	1.00	0.86
(19) Average daily wind movement in miles	29.2	27.8	29.4	

There is no appreciable error if we write $\Delta(LER_w) = L\bar{E}(\Delta R_w) + (L\Delta E)\bar{R}_w$ where the bar indicates an average for the pan and lake. The second law of thermodynamics requires that $L\bar{E}(\Delta R_w) + \Delta b \leqq \Delta B$, and we know that $(L\Delta E)\bar{R}_w$ must be only a minute fraction of the total energy of evaporation, because ΔE is only a small fraction of E, and R_w is of the order of magnitude of one per cent [10, p. 132]. If then, we apply the entire correction ΔB, computed on the basis of STEFAN'S law [15, p. 529], we shall have an overcorrection, and since this overcorrection is itself remarkably small [Table 2, line 5], whatever error it may contain on account of radiative diffusivity must be extremely small. This conclusion is borne out by the experiments of CUMMINGS and RICHARDSON [15], although further investigations, bearing more directly on the point, are desirable.

The presence of R on both sides of equation (13) tends to reduce that part of the total error which is due to indefiniteness in the magnitude of J, since $\bar{R}$ is positive for both pan and lake.

A reliable estimate of the error in the final determination of evaporation from a large body of water may be obtained from a consideration of the separate errors entering at the various stages of the computation, and, as the limits of uncertainty of each step are contracted, the uncertainty of the end-result is decreased.

Practical and theoretical uses of the energy-evaporation equations--Equation (10) thus possesses two characteristics which seem to be worthy of note.

(1) It is entirely practical for the actual determination of evaporation whether such determination is needed for utilitarian or other reasons. It is at least potentially adaptable to any economic conditions. Thus, if detailed knowledge of R is too costly, a suitable average, based on accumulated experience, can be used. For Bear Lake in 1937 the seasonal average $\bar{R}$ may somewhat, though not greatly exceed those given by SVERDRUP [5, p. 64] for the ocean. It should be noted, however, that this value is weighted so as to take account of diurnal variations in atmospheric instability, while his presumably are not.

If insulation of the pan is too expensive, uninsulated pans can be used provided suitable comparative tests have previously been made. This is no drawback, because the characteristics of any instrument should always be known before the instrument is extensively used. If funds are not available for finding the lake S, it can, for time-intervals as long as a month, be estimated without serious error, especially during the time of the year when the evaporation-rate is large. For a complete annual cycle, S is obviously zero.

In oceanographic work, there may be confusion between S and C, because of ocean currents, but even this difficulty can be overcome if sufficiently generous material-resources and equipment are available. There are no other oceanographic obstacles to the use of the equation, provided an insulated pan can be employed successfully. This will certainly be the case in the vicinity of islands. Equation (10) can thus be used for calibrating turbulent transfer procedures. Of course, as in many oceanographic observations, the precision may not be as high as we should like, but that is a limitation on ocean-work in general, and not on the solution of this particular problem.

(2) The equation is related to other bodies of knowledge in an advantageous way, not only from the standpoint of theory, but from that of observation as well. Thus there are many reasons for needing the temperature-data on which our knowledge of S depends. This is true for both lakes and ocean. Moreover, the equation renders possible an intelligent use of vast accumulations of pan-records, provided the thermodynamic behaviour of the pan is known. If this knowledge is not to be had, then the records are utterly worthless, for they can never be objectively interpreted on any other basis. The wet-and dry-bulb temperatures have many uses. After a little more experience with the equation, it probably can be used in connection with routine pyrheliometer-readings, which are rapidly becoming more numerous, but are already sufficiently extensive to have genuine significance.

Anyone interested in empirical equations for expressing evaporation in terms of wind and humidity, will profit by examining equation (6) and also by combining equations (1) and (10) and rearranging in various ways for comparison with the empirical equations under consideration.

Experimental verification--It is, of course, desirable to test such arguments as have been given, by comparison with actual observation, and for that purpose, the experiments of CUMMINGS and RICHARDSON [15] were conducted.

When the BOWEN equation was used, the two sides of equation (13) of the present paper were found to balance within less than three per cent at Pasadena and less than two per cent at Fort Collins. Nevertheless, the close approach to equality of the pan and tank $\overline{R}$'s prevented the experiment from being a severe test of the BOWEN equation on its own account, although, if the large departure from fact which has been ascribed to the equation were a reality, it seems as if the discrepancy should have appeared. The difference in the $\overline{R}$'s was only 0.03 at Pasadena, but it was 0.14 at Fort Collins.

Various types of material such, for example, as that provided by SVERDRUP [5, Chap. IV] can, moreover, be employed for tests of inferences that may be drawn from the energy-equations so that if there actually were any considerable departure from observation, a sufficiently accurate numerical estimate of the discrepancy could be found with remarkable ease. Yet nothing of the kind appears to have been reported.

There is, of course, an element of diffuseness in most attempts to employ data that are published before definite plans for their use are worked out, because unknown quantities of energy are likely to be involved. Nevertheless, if the data are carefully selected with this limitation in mind, the indeterminate quantities of energy can be reduced sufficiently to insure that a large error in the equations themselves would appear if it existed.

The following example, though not conclusive in itself, will serve to illustrate the point. Personal judgment suggests that the resultant radiation at San Bernardino, California, is about the same as at Lake Elsinore, approximately 30 miles away. During August, 1938, a thermally insulated pan at San Bernardino lost 8.4 inches, while the lake lost 7.8 inches [11, Table 4]. A Weather Bureau pan on the lake shore lost 10.5 inches. August is a good month for comparison, not only because of the large evaporation, but also because of the small change in heat storage. Since Elsinore is shallower than Bear Lake, $\overline{R}$ would, presumably, be smaller.

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APPENDIX I

Justification of the steady state--For estimating the order of magnitude of the time-lag, we can disregard wind, because the question is one of diffusion upward across the wind-path. So far, then, as the specific purpose in hand is concerned, we may assume stagnant air for an indefinite distance upward.

Since any small temperature-change at the surface may be regarded as a segment of a simple harmonic variation, we may profitably investigate the upward propagation of a temperature wave, or more strictly, of a wave for each of the energy-components. The two waves will, as is well known, travel in accordance with the differential equations

$$\partial\theta/\partial t = D_L \, \partial^2\theta/\partial x^2$$

$$\partial\phi/\partial t = D_S \, \partial^2\phi/\partial x^2$$

in which t is the time.

It can easily be shown that the wave length, λ, is given by

$$\lambda^2 = 4\pi DT$$

where T is the period of the temperature-cycle, and D is the diffusivity for either form of energy, since for our present purpose, the two diffusivities may be regarded as equal. Substituting D = 0.2 cm^2/sec, and $4\pi T = 10^6$ sec. for a daily variation, gives

$$\lambda = 10^3\sqrt{0.2}, \text{ or more than 400 cm.}$$

This means that the temperature wave travels at a rate of more than 400 cm per day, which would get it through the laminar layer in about one minute. Since the amplitude is never large enough to make the water-temperature change appreciably during a time-interval of one minute, we may neglect time-lag entirely. The very large magnitude of the turbulence-coefficient eliminates any need for concern above the laminar layer.

This conclusion is supported by the fact that some of the most careful analyses of the evaporation problem that have ever been made, have assumed a steady state.

The foregoing may not apply to a narrow fringe skirting the windward edge of the lake, and having a width equal to or less than y_1. Over this fringe, the oncoming air is, after sudden contact with the water surface, in process of coming into equilibrium.

The time required for the effect to reach a height x, is given by $x^2 = 4$ Dt [10, p. 227, eq.(16)]. If we choose x = 1 cm and D = 0.2 cm^2/sec, t = 1.2 sec. As a basis for comparison in exploring the field empirically, x_2 = 1 cm is high enough.

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SOIL-PERMEABILITY AS A CRITERION FOR DRAINAGE-DESIGN

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Abstract--The design of drainage facilities for agricultural land requires quantitative evaluation of (1) the water involved; (2) the permeability of the materials through which the water flows; (3) the dimensions of the aquifer; and (4) the position of the water table. This paper details techniques utilized in the determination of the coefficient of permeability in the laboratory and in the field. It further presents the need for rapid techniques of indirect determination of permeability, but recognizes the limitations of this method. The application of the coefficient of permeability in the analysis of a drainage problem or facility is outlined, and a formula for the spacing of tile-drains utilizing the coefficient of permeability is presented.

Introduction--Sub-surface drainage design requires the determination of four fundamental physical factors: (1) Q, the quantity of water to be drained; (2) P, the coefficient of permeability or the transmission-constant of the material which is to be drained, and particularly the aquifer or drainage medium; (3) I, the hydraulic gradient; (4) A, the cross-sectional area of the material through which the water flows. In order to advance drainage design beyond the point of "trial and error" or empirical design based on experience, quantitative values must be placed upon these factors.

Without quantitative determinations, field estimates of permeability are difficult and often dangerously misleading. Because considerable variability exists in stratification sequences and character of the materials in the west and southwest regions of the United States, a reasonably rapid, yet accurate method of determining the permeability coefficient is highly desirable. When these techniques are satisfactorily developed, they may be applied directly to drainage-design.

Procedure--There are two approaches to this task; (1) The direct measurement of permeability in the laboratory by using samples of the material prepared by some standard method or by taking undisturbed core samples; (2) the indirect measurement of permeability in the laboratory from analyses of the physical properties of the materials. Investigations of this nature have been and are being undertaken; however, no methods have been perfected to the extent that they may be universally applied to all localities and conditions without prior measurements of the permeabilities and comparison with these tests. Some of these endeavors have employed moisture equivalent, mechanical analyses [see 1 of "References" at end of paper], percentage of clay, moisture percentage retained against a specified tension or tensions [2], the moisture desorption flex point, and many others. Some workers have introduced values, such as moisture equivalent, directly into a tile-spacing formula [3].

The nature of the sediments that are to be studied must be considered in the design of a permeameter. Of primary importance, especially in the Imperial Valley, are those strata which provide a medium through which the water may flow at a satisfactory rate toward a drainage-facility. Such strata may be designated as aquifers. Permeability of these aquifers may range from a minimum of possibly 0.1 cm per hr to 300 cm per hr or more. Materials having a permeability within this range are necessarily within the light textural groups, possibly between very fine sandy loam and medium sand. Procurement of numerous undisturbed samples is difficult and their exclusive use is impractical, especially since the aquifer is usually saturated and may be at considerable depth. Samples can more readily be obtained in a disturbed state by the use of drilling equipment and then prepared for measurement of permeability under a standard procedure.

Four steps are then in order for the determination of permeability for extensive application to drainage design: (1) the measure of permeability of disturbed samples; (2) measure and correlation of permeability of undisturbed samples taken both parallel to and normal to the bedding plane; (3) check of laboratory permeability with field permeability, as described below; (4) development of an indirect method for rapidly evaluating the permeability coefficient to be applied directly to drainage facility planning.

Techniques--A permeameter was developed for use under conditions as described. It may be used either for prepared or undisturbed samples and is most suitable for samples having permeability values between 0.01 and 300 cm per hr.

Although the permeameter used is basically somewhat similar to those used by laboratories of the United States Geological Survey, the Corps of Engineers of the United States Army, and others, the dimensions and detail of construction differ considerably.

The permeameter consists of a brass soil cylinder 5 cm in diameter and 6, 10, or 20 cm in length. The ends are closed by a brass disc fluted on the inside and provided with openings to allow water to move into and out of the core. A brass screen and filter paper are held securely against the soil-column and the unit is held in place by connecting rods. Three or more manometer openings are drilled in the cylinder wall. These are equally spaced along the cylinder, but rotated 60 or 90 degrees to minimize the effect of possible leakage between the cylinder wall and the soil sample. Each manometer opening is threaded so that a take-off tube may be screwed into position. When undisturbed cores are taken, the tubes are replaced by short plugs that fit flush with the interior and exterior walls. A very thin packing of glass wool is forced lightly into the threaded end of the manometer take-off to prevent sloughing of the sample into the manometer tube (see Fig. 1). For convenience of reading, glass manometers connected to the take-off tubes with rubber tubing are mounted on a panel marked off in millimeters (see Figs. 2 and 3). The effluent is measured in small burettes. Lack of temperature-control necessitates periodic readings (as opposed to cumulative readings) and correction for temperature. By using more than two manometers it is possible to obtain separate coefficients for the several sections of the soil column. This is of special importance when measurements are being made on undisturbed samples. The head of water applied to the permeameter is maintained at a constant level approximately twice the length of the soil column, but may be raised or lowered depending upon the permeability of the material. When readings are not in progress the effluent is allowed to drain off. In this way, movement through the permeameter is continuous.

The quality and quantity of dissolved solids present in the water used in the permeameters is extremely important. Studies made by BODMAN [4], FIREMAN [5], REITEMEIER and CHRISTIANSEN [in preparation], and others, have shown the importance of the water composition as related to both permeability and infiltration. To minimize this phenomenon, the water used duplicated the natural ground-water as nearly as practicable. The addition, exchange, or leaching of salts by water may alter the degree of flocculation of the soil sufficiently to materially affect the results. The greater the percentage of fines present in a sample, the more marked are the changes in permeability that may occur.

The actual permeability-run offers several complications. It has been found that usually the permeability-record progresses through three periods: (1) a period of increase; (2) a period of relative constancy; and (3) a period of reduction. The length of time and the amplitude of these changes appear to depend upon the character of the material. The period of rise is probably due to the dissolving of air entrapped in the soil core. After the period of decrease has begun, the introduction of a sterilant such as potassium permanganate or mercuric chloride restores the permeability rate to a higher level suggesting micro-organism growth to be the cause. These findings are in agreement with the conclusion of CHRISTIANSEN [6]. The coefficient of permeability most closely conforming to conditions in the field is established by averaging the readings during the period of constant permeability. It is extremely important that a permeability-run be continued until this period is reached or the results obviously will be in error. Time required to reach this period varies from 100 to 400 hours.

The procedure for converting the laboratory data to the coefficient of permeability utilizes an adaptation of DARCY'S law, $P = Q/IA$, in which P = permeability coefficient, Q = quantity of water discharged per unit of time, I = hydraulic gradient, and A = cross-sectional area of sample.

Substituting the values $Q = V/t$ and $I = (h_1 - h_2)/\ell$, where V = volume discharged in cc, t = time in hours, ℓ = length of soil column (or portion involved) in cm, and $(h_1 - h_2)$ = head differential in cm; incorporating a corrective factor for temperature, C_t, the formula for permeability coefficient expressed in cm per hr becomes,

$$P = V\ell C_t / t\,A(h_1 - h_2)$$

Laboratory permeability results--During the past two years 170 permeability runs have been made involving only lighter textured sediments of the Imperial Valley, and including both prepared and undisturbed samples. Evidence indicates that the coefficient of permeability is higher in an

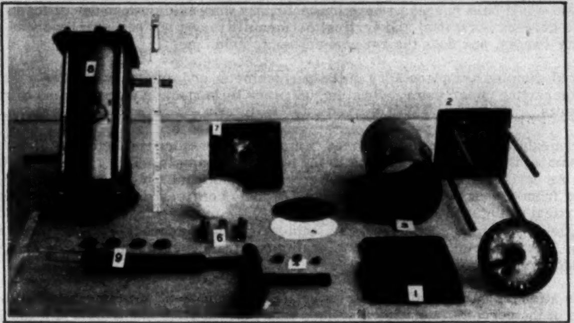

Fig. 1--Parts of the permeameter assembly--(1) Rubber gaskets, (2) lower plate with bolts, (3) permeameter tube, (4) manometer outlet caps, (5) brass screen and filter paper, (6) manometer take-off tubes, (7) assembled top plate, (8) unit assembled, (9) discharge unit

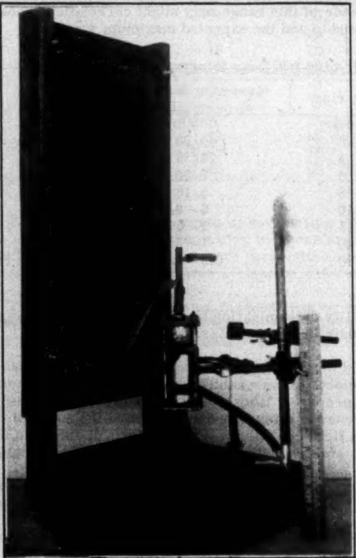

Fig. 2--Rear view of permeameter assembly

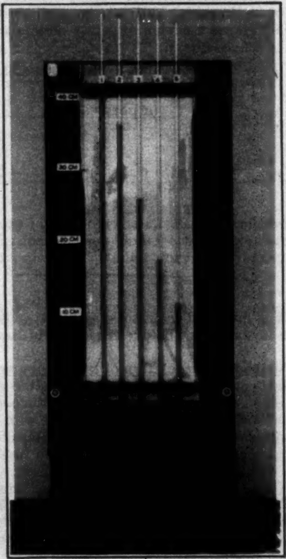

Fig. 3--Front view of permeameter assembly, showing manometers

undisturbed sample taken parallel to the bedding plane than in one taken normal to the bedding plane with an approximate ratio of 1.7 to 1.0. Obviously this ratio is but an average of conditions in Imperial Valley and is applicable only to that area and within the narrow textural limits under investigation. Close visual observation of the sediment both in the field and laboratory indicate the possible divergence from this ratio. These differences are caused either by macro-stratifications of coarser and finer materials or a lath-like pattern of angular sand grains. It is not likely that the ratio would hold in areas where the materials were laid down under different conditions. A high ratio between horizontal and vertical permeability does not necessarily occur in the higher permeability-ranges, nor does the reverse appear to hold true.

Prepared samples are placed dry in the permeameter and are tamped under a standard procedure. Compacting under water, vibrating, and other techniques have been found to give unsatisfactory results.

The permeability found in the prepared sample is more comparable to that of the vertical undisturbed sample than to the higher rate in the horizontal sample. This ratio varies between 1:1 and 0.5:1. As horizontal permeability is of greatest significance in drainage design, permeabilities derived from prepared samples are about 1/2 to 1/3 of field values. However, as the ratio between vertical and horizontal permeability lowers, the prepared sample permeability more closely reflects field conditions. This ratio can, with reasonable accuracy, be established by visual observation or by a trial run in a particular locality or stratum. Wide application of this ratio obviously would not be advisable.

Various attempts have been made to correlate the coefficient of permeability with texture. A comparison of the percentage of clay fractions with permeability was tried and found unsatisfactory. A second comparison was tried using the total silt and clay fractions. This correlation was decidedly better. It was found that within the permeability range from 1.0 cm per hr to 50 cm per hr with the silt-clay fractions ranging from 30 per cent down to 2 per cent a general relationship held. It is questionable whether such a relation will hold over large areas; it may be only a local condition of the Imperial Valley. For sediments outside of this range only slight correlation appears. Table 1 shows a series of points on this relationship and the expected maximum variation.

Table 1--Relationship of silt-clay fractions to permeability

Mean coefficient of permeability	Silt-clay	Maximum deviation of permeability
cm/hr	pct	cm/hr
50	2	40-90
20	4	15-35
11	6	8-20
7	8	5-15
6	10	5- 9
3	15	2- 5
2	20	1- 3
1	30	0.5- 1.5

It is apparent from this table that permeability determination by indirect techniques requires more investigation before it may be utilized widely in drainage design.

Method of correlation of laboratory and field permeability--As explained above there are various laboratory methods of evaluating the coefficients of permeability of aquifers. Not only must there be a correlation between undisturbed and prepared laboratory samples, but there must also be a check of the laboratory findings with field coefficients, in order to be sure the range of coefficients secured in the laboratory compare with field conditions. Furthermore, if and when these laboratory coefficients are applied to field problems, variation or deviation should be recognized.

There are several methods of securing field coefficients of permeability. These methods are all discussed by WENZEL [7]. Several formulas based on the flow of water into discharging wells can be used either directly or indirectly for the determination of permeability. A basic assumption of these formulas is that the cone of depression around a discharging well has reached equilibrium (steady flow).

A simple development of one of these formulas has been used and under certain conditions coefficients of permeability can be obtained which are consistent.

To obtain data in the field, borings are made about a well-site to determine the scope and depth of the aquifer-material. A gravel-envelope well tapping the aquifer is then put down. This well consists of a seven-inch auger-hole bored down through the aquifer to the barrier below. A sand point is lowered into the hole and enveloped with gravel. This type of well can be put in economically and quickly.

A pattern of piezometers [8] is then installed, with spacing of 5, 10, 20, 40, and 80 feet out from the well in the four cardinal directions.

The well is pumped with a low-velocity pump for 48 or 72 hours. When the cone of depression around the discharging well has reached equilibrium, all the control factors needed for the determination of the field coefficient of permeability are measurable. Q is measured as the discharge from the pumped well; I, the hydraulic gradient, is indicated by the piezometric records; and A, the cross-sectional area of the aquifer is determined between the boundary limits of barrier below and drawdown cone above. P, coefficient of permeability, is then calculated by the formula

$$P = (Q \log_e r_2/r_1)/[2\pi(h_2 + h_1)(s_1 - s_2)] ,$$

where Q = discharge in gal per day, r_1 and r_2, respectively, radial distances in feet to two sets of piezometers, h_2 and h_1 = thickness of aquifer in feet a r_1 and r_2, and s_1 and s_2 = drawdown in feet at r_1 and r_2. The results of some field trials are shown in Table 2.

Table 2--Summation of a field permeability trial

Date	Time	r_1	r_2	Permeability	Notes
1944	h m	ft	ft	cm/hr	
Apr. 4	9 15	5	10	5.84	
	9 15	5	20	6.00	
	9 15	5	40	6.34	
	9 15	10	20	6.16	
	9 15	10	40	6.58	Eady farm trial piezometers terminating at 6-1/2 feet below datum line.
	9 15	20	40	7.26	
Apr. 5	7 45	5	10	6.05	
	7 45	5	20	6.38	
	7 45	5	40	7.17	
	7 45	10	20	6.67	
	7 45	10	40	7.83	
	7 45	20	40	9.27	

To simplify the experiments of correlating laboratory and field coefficients of permeability, only aquifers underlain by tight clay barriers and having considerable homogeneity have been used. Samples are collected and rates of percolation are determined in the laboratory for comparison. The aquifers studied have given a close correlation.

The procedure for deriving permeability by laboratory technique requires that the variations in the aquifer-permeability be measured and prorated in order to obtain a comparable value to the field measurement. The procedure is shown in Table 3.

Table 3--Procedure for deriving permeability from laboratory data

Aquifer component	Coefficient of permeability,P	Average thickness	Part of aquifer	Weighted value (P x)
	cm/hr	feet	pct	(pct)(cm/hr)
A	5.60	0.27	9.15	51.24
B	6.70	2.33	78.98	529.17
C	1.47	0.35	11.87	17.45
Total		2.95	100.00	597.86

Then prorated permeability, 597.89/100 = 5.98 cc/hr

Application--If, as detailed in the foregoing discussion, a method or methods can be perfected for determining reasonably and accurately the coefficient of permeability of a soil, then the drainage engineer has obtained a tool to use in the design of a drainage system.

The coefficient of permeability can be used in determining the amount of seepage from canals. After a strata-survey determines the extent of the aquifer through which seepage is taking place and a piezometric study establishes the hydraulic gradient of flow, the coefficient of permeability will complete the data necessary for calculating the amount of seepage.

The coefficient of permeability can be used in the planning and design of sump and relief wells. With the permeability of the aquifer known, a prediction can be made as to the shape of the drawdown curve around a sump or well.

One of the more important uses of the coefficient of permeability in the solution of drainage problems is in the development of criteria for the spacing and depth of a tile-system. An attempt has been made to establish a formula for spacing tile-lines using permeability of the aquifer as a criterion.

Returning to the modified DARCY law, $Q = PIA$, it can be said that if Q, P, and A are known it is possible to solve for I, the hydraulic gradient. In the following hypothesis the drawdown or hydraulic gradient that might occur about a tile-line or lines has been synthesized. Furthermore, when it has been synthesized, prescribed limits to this drawdown are established for any site-circumstance, and a determination is made of the spacing of the lines. This formula is open to question. Several empirical assumptions are made. However, a delineation has been made of its limitations with field tests on existing tile-systems and laboratory tests in a sand-tank model.

A basic assumption has been made in developing this formula. In Figure 4, where lines are spaced a definite distance, S, apart, all the flow to the tile is due to the removal of water from a strip extending a distance S/2 on each side of the tile-line. The assumption is that the horizontal flow at any distance, x, is proportional to the distance from a point midway between the tile-line where the flow is zero. Thus when $x = S/2$, Q_R (flow toward the tile-line from the right) is zero. When $x = 0$, flow toward the tile-line is one-half the flow in the line or $Q/2$.

Thus at any unit length at right angles to the tile-line $Q_R = (Q/S)\ (S/2-x)$.

Referring again to Figure 2, I (hydraulic gradient of the drawdown curve) $= dy/dx$, A (cross-sectional area of flow) $= y \times \ell$, and P = (coefficient of permeability of the aquifer material). Letting $\ell = 1$ and substituting these in DARCY'S law, the expression would be

$$Q/S\,(S/2-x) = P\,y\,(dy/dx),$$

from which

$$Q/2PS \int (S-2x)\,dx = \int y\,dy$$

Integrating $-(Q/8PS)\,(S^2 - 4Sx + 4x^2) = y^2/2 + C$. When $x = 0$, $y = a$, so that $C = -QS/8P - a^2/2$.

Substituting for C, $-Q(S^2 - 4Sx + 4x^2)/8PS - y^2/2 + (-QS/8P - a^2/2)$, and solving this equation for P

there is obtained $P = Q(Sx - x^2)/\,S(y^2 - a^2)$. When $x = S/2$, $y = b$, $P = QS/4(b^2 - a^2)$, and finally $S = 4P(b^2 - a^2)/Q$.

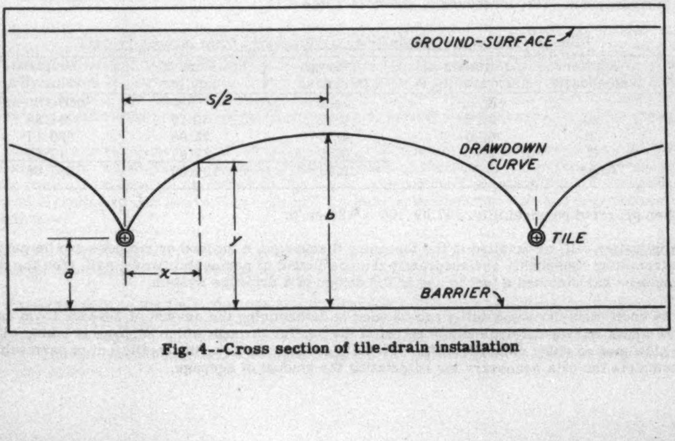

Fig. 4--Cross section of tile-drain installation

In applying this formula to the design of a drainage system there will be quantitative values for

(1) P, the coefficient of permeability,
(2) Q, the amount of water to be drained out of the soil profile, per unit of time,
(3) a and b, the limits of the drawdown curve as delineated by a strata survey of the site, the circumstances, and the objective to be achieved.

A calculation is then made for the spacing of the tile system.

Checks of this formula have been made in both the laboratory and the field. In the field the drawdown curves over existing tile-lines were charted. Spacing was then calculated by the formula, since P, b, a, and Q were all measurable in the field site. Good correlations were obtained when computed and actual spacings were compared.

Table 4 is a tabulation of the correlations made on the field sites of actual tile installations. In the laboratory, checks of the formula are in the preliminary stages in a large sand-tank where all the variables become measurable.

Table 4--Summary of data on tests of tile-drains

Trial	Date	Tile output, Q	Q	Actual spacing of lines	b_1	b_2	$\frac{b_1 + b_2}{2}$	a	$b^2 - a^2$	P	Computed spacing
	1943	gpd	gpd/ft	ft	ft	ft	ft	ft	ft^2	gpd/ft^2	ft
1	June 23	8208	6.42	600	5.18	5.00	5.09	2.65	18.87	60.	705
2	June 24	7488	5.84	600	4.80	4.52	4.66	2.65	14.67	60.	605
3	June 25	43200	33.8	300	8.03	6.47	7.25	2.65	45.57	60.	324
4	June 26	30816	24.1	300	7.10	5.94	6.52	2.65	35.47	60.	354
5	June 27	19440	15.2	350	6.24	5.36	5.80	2.10	28.19	55.	410
6	July 16	14550	11.4	550	6.42	6.73	6.57	3.22	32.82	53.	610
7	July 19	28000	21.9	500	7.26	7.84	7.55	3.05	47.70	63.	548
8	July 20	18000	14.1	400	6.48	6.24	6.36	1.85	37.08	41.	428

It is not likely that this formula will be applicable to all the drainage problems involving tile-spacing. Stratified aquifers present formidable difficulties. However, the formula gives satisfactory results for homogeneous soils with a barrier below. The work of applying coefficients of permeability to the solution of drainage problems is only in the development stage and it remains to be seen whether applications can be made to fit the multitude of problems anticipated in the stratified soils of Imperial Valley.

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GREAT SALT LAKE: A SELECTED BIBLIOGRAPHY WITH ANNOTATIONS

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Early reports

Explorers began to push into the vast uncharted areas of the West in 1804, when Captains LEWIS and CLARKE ascended the Missouri River, crossed the Rocky Mountains into the headwaters of the Columbia River, and followed that stream to the Pacific Ocean. The honor of being the first white man to see Great Salt Lake is claimed for a number of explorers and trappers who visited the region in the twenties and thirties of the Nineteenth Century. Among these were ETIENNE PROVOT and JAMES BRIDGER, who were in the region in 1824-25, each quite unaware of the other's activities and discoveries.

In 1833 Captain B. L. E. BONNEVILLE dispatched a party from his camp at Green River, Wyoming, for the purpose of exploring Great Salt Lake. This party attempted to make a circuit of the lake, chart its outline, and trap all the streams en route, but the attempt was abandoned because the great barren salt plains west of the lake were so hazardous that the party was in grave danger of perishing.

An account of the BONNEVILLE Expedition is given in the following publication:

1832-33: WASHINGTON IRVING, The Rocky Mountains; or scenes, incidents and adventures in the Far West; digested from the Journal of Captain B. L. E. BONNEVILLE of the Army of the United States, and illustrated from various other sources. In two volumes. Philadelphia; Carey, Lea, and Blanchard, 1837.

Great Salt Lake was called Lake Bonneville by IRVING, but its existence was well known to the traders and trappers for many years before the coming of Captain BONNEVILLE.

The first survey of the lake was made by Captain JOHN C. FREMONT, who led an exploring expedition into the Great Salt Lake Region in 1843. In the course of this survey, the Captain hoped to find vegetation and water on one of the larger islands in the lake, and finding neither he named the island Disappointment Island. Subsequently, it was named Fremont Island, in his honor. He named Antelope Island because he found antelope there, which served to replenish his depleted store of food. The lake itself remained officially unnamed until FREMONT'S use of the popular and logical title, Great Salt Lake, became officially accepted.

FREMONT'S printed report is entitled:

1843: J. C. FREMONT, Report of the exploring expedition to the Rocky Mountains in the year 1842, and to Oregon and North California in the years 1843-44. Senate Doc. 174, 28th Cong., 2nd Sess., 1845.

In April, 1849, another expedition was organized under the leadership of Captain HOWARD STANSBURY, "having for its object a survey of the Great Salt Lake and an exploration of its valley." The report of this expedition is entitled:

1849: HOWARD STANSBURY, Exploration and survey of the valley of the Great Salt Lake of Utah, including a reconnaissance of a new route through the Rocky Mountains. Senate Executive Doc. 3, special session, March 1851, Philadelphia; Lippincott, Grambo, and Co., 1852.

This expedition reached the Salt Lake Valley August 27, 1849, and in order to ascertain the general features of the lake and "gain some knowledge of the means and appliances necessary to carry on the survey with safety and expedition," STANSBURY equipped it to make a reconnaissance of the deserts around the western shores of Great Salt Lake. The party set out on the afternoon of October 19, 1849, from the ford of the Bear River and proceeded counter-clockwise around the lake. After numerous hardships and sufferings and loss of mules from lack of fresh water, the party finally reached Salt Lake City November 7, 1849, "being the first party of white men that ever succeeded in making the entire circuit of the lake by land. Attempts had, in early times, been made to circumnavigate it in canoes, by some trappers in search of beaver; but they all proved unsuccessful from want of fresh water."

During the summer of 1850 the lake-survey was completed. The shoreline at that time, exclusive of offsets, was 291 miles and the shoreline of the islands in the lake totaled 96 miles. STANSBURY is credited with having made the first complete exploration of Great Salt Lake and also with having made the first written comment on the evidence of the former existence of a vast body of water such as prehistoric Lake Bonneville.

In 1867 a geologic and topographic reconnaissance-expedition took the field "to examine and describe the geological structure, geographical conditions, and natural resources of a belt of country extending from the one-hundred-and-twentieth meridian eastward to the one-hundred-and fifth meridian of longitude, along the fortieth parallel of latitude with sufficient expanses north and south to include the lines of the Central and Union Pacific railroads, and as much more as may be consistent with accuracy and proper progress."

The main results connected with this expedition are seven quarto volumes and one atlas, published as:

1869: CLARENCE KING, United States Geological Exploration of the Fortieth Parallel. volume 2, Descriptive Geology, Govt. Print. Off., Washington, 1877.

Great Salt Lake was surveyed and studied by this expedition in 1869. The results of the work are set forth on pages 431-439 of volume 2 above mentioned.

Notes of Dr. A. S. PACKARD, Jr., "on the supposed ancient outlet of Great Salt Lake" are recorded in Bulletin No. 5, Second Series, January 8, 1876, of the United States Geological and Geographical Survey of the Territories, F. V. HAYDEN, U. S. Geologist in Charge, Washington, Government Printing Office, 1875. That same year (1876) "The Great Salt Lake in former times," also by PACKARD, appeared in American National, volume 10, pages 675-681.

As one of the features of the "Expedition for Geographical Surveys West of the 100th Meridian in Colorado, New Mexico, Utah, California, Nevada, Oregon, and Washington in 1878," a party in charge of Second Lieutenant WILLARD YOUNG, Corps of Engineers, was entrusted with the survey of Great Salt Lake. This included a meander of its shoreline and of the islands, the gaging of inflowing water, the determination of the amount of surface-evaporation, and the rise and fall of the lake, as well as the topography of the country immediately bordering the lake and the islands. Work was continued on this survey from April 22 to June 30, 1879, and a report covering it is contained in the Annual Report, 1879, of this expedition.

For at least ten years prior to 1881, G. K. GILBERT, a geologist attached to the geographic corps of Captain GEORGE M. WHEELER of the United States Engineers, devoted much time to a study of Lake Bonneville. When the present Geological Survey was organized he became a member of it and had already accumulated a considerable body of facts and published an outline of a report on this ancient lake. In 1881 he was engaged in the preparation of "Lake Bonneville," Monograph 1 of the Geological Survey, the principal conclusions of which are set forth in the Second Annual Report, 1880-81, of the Geological Survey--"Contributions to the history of Lake Bonneville, by G. K. GILBERT," pages 169-200. The manuscript of the monograph was transmitted to the Director of the Survey in June, 1889, and was printed in 1890.

A partial discussion of the deformation of the plane of the Bonneville shoreline was presented to the American Society of Naturalists at its Boston meeting in 1885. "The ancient outlet of the Great Salt Lake," by GILBERT, was published in the American Journal of Science, volume 35, pages 256-259, 1878, and his "Outlet of Lake Bonneville" was published in the American Journal of Science, volume 35, pages 341-348, 1880.

"Lakes of North America" and "Lakes of the Great Basin," both by ISRAEL C. RUSSELL, are publications of the early 80's that devote some discussion to the Great Salt Lake and its predecessor, Lake Bonneville.

A digest of these early reports is published in the following paper:

1939: FREDERICK J. PACK, Lake Bonneville, a popular treatise dealing with the history and physical aspects of Lake Bonneville. Bulletin of the University of Utah, volume 30, no. 4, 1939.

Animal life

Ordinary aquatic forms of life do not exist in Great Salt Lake because of its intense salinity. However, investigators have reported no less than nine or ten species of microscopic animals--one a crustacean, three flies, and five or six protozoans. A species of brine shrimp is one of the animals of greatest significance and abundance. At times it congregates in such numbers as to tint the water over wide areas. Algae are exceedingly abundant also. These are often noted drifting before the wind in long irregular streams on the lake surface. They commonly accumulate along the shore and in decaying contribute to the characteristic fetid odor of the lake-shore facies.

During some years long windrows of the puparia of certain flies and countless swarms of the adult flies are seen resting on the water-surface or flying close to it.

Myriads of water-fowl and shore-birds inhabit the islands in Great Salt Lake and the northern, eastern, and southern shores. Large colonies of nesting water-birds are summer-residents on several of the small islands, and the Bear River marshes, from time immemorial, have been tenanted by great numbers of water-fowl. This area is now one of the nation's largest water-fowl refuges.

Reports pertaining to the animal life associated with Great Salt Lake are listed as follows:
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1942: WM. H. BEHLE, The colonial nesting birds of Great Salt Lake, Bull. Min. Soc. Utah, v. 3, pp. 59-63, 1942.
1944: DAVID T. JONES, Two protozoans of Great Salt Lake, Bull. Univ. Utah, v. 35, Biol. Ser., v. 8, No. 4, 1944.
1945: DAVID T. JONES, Protozoa in Great Salt Lake, Arrow Press, Salt Lake City, 1945.

Plant life

Plant life in Great Salt Lake comprises organisms of low evolutionary position. Of the plants that have been listed, 13 species are algae, 12 are bacteria, and 62 are diatoms. Since 1871 botanists have from time to time examined plant material from the lake. They are not agreed on the number or kind of algae that live in the brine because certain forms are tolerant of the lake-water and others are fresh-water species that have been carried into the lake and preserved. One investigator could only be sure that five colonial forms of blue-green algae were present instead of 13 as previously described.

Reports by various authors on their research-work on this subject are listed below:
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1924: ELFREDA FREDERICK, The bacterial flora of Great Salt Lake, thesis, Univ. Utah, 65 pp., May, 1924.

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1936: RUTH PATRICK, Some diatoms of Great Salt Lake, Bull. Torrey Bot. Club, v. 63, pp. 157-66, 1936.
1937: C. E. ZOBELL, D. Q. ANDERSON, and W. W. SMITH, The bacteriostatic and bactericidal action of Great Salt Lake water, J. Bacter., v. 33, pp. 253-262, 1937.
1942: SEVILLE FLOWERS, Plant life of the Great Salt Lake Region, Bull. Min. Soc. Utah, v. 3, pp. 36-56, 1942.
1942: W. P. COTTAM, The flora of Great Salt Lake, Bull. Min. Soc. Utah, v. 3, pp. 33-35, 1942.

Chemistry

The water of Great Salt Lake is intensely salty. The saline matter has nearly the same composition as that of the ocean, but its salinity is from four to ten times greater. The percentage of salinity varies inversely with the changes in the level of the lake or its volume, except when they are so low that the water becomes saturated with salt. Since late in 1933 the lake has been saturated with respect to sodium salts.

Analyses of the water have been made from time to time since 1869. From that time down to 1913 no less than eight analyses were made and published in the following reports (The dates at the left are those of collection of samples. The persons named are generally the analysts, not necessarily the authors of the reports in which the analyses are published.):
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1900: J. E. TALMAGE, The Great Salt Lake past and present, pp. 65-68, Pub. Deseret Book Store, Salt Lake City, 1900.
1930: A. A. L. MATHEWS, Origin and growth of the Great Salt Lake Oolites, J. Geol., v. 38, pp. 633-642, 1930.
1938: A. J. EARDLEY, Sediments of Great Salt Lake, Bull. Amer. Assn. Pet. Geol., v. 22, No. 10, pp. 1305-1411, 1938.
1938: T. C. ADAMS, Recent depositions of salt from Great Salt Lake, J. Geol., v. 46, pp. 637-646, 1938.

Economic resources

Chemical analyses of the water of Great Salt Lake and studies of the sediments of the lake have from time to time incited investigators to suggest chemical industries to develop and utilize the vast amounts of salts that are available from these sources.

Suggestions relative to economic values of these resources and their utilization in chemical industries and other commercial enterprises are indicated in the following published reports:
1927: RALF R. WOOLLEY, Some salient features connected with the fluctuations in level of Great Salt Lake, Utah Engr., v. 1, No. 8, pp. 1-3, 1927.
1927: R. A. HART, Some human influences on the oscillations and trend of Great Salt Lake, Utah Engr., v. 1, No. 10, pp. 1-3, and 6, 1927.
1929: G. M. STRATTON, Utah's salt industry, Utah Engr., v. 3, No. 5, pp. 1-3, 1929.

1932: T. C. ADAMS, Some hydrologic features of Great Salt Lake, Utah Engr., v. 6, No. 5, pp. 1-3 and 5, 1932.

1936: A. J. EARDLEY, Oil and gas possibilities in the Great Salt Lake Basin, Utah. Acad. Sci. Arts, and Letters, v. 13, pp. 61-80, 1936.

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1942: JUNIUS J. HAYES, Great Salt Lake and its economic importance, Bull. Min. Soc. Utah, v. 3, pp. 11-23, 1942.

1944: RALF R. WOOLLEY, An engineer looks at Great Salt Lake, Civ. Eng., v. 14, pp. 332-334, 1944.

Archeology in the Great Salt Lake Area

Archeologists now have evidence which leads them to the belief that man has inhabited various parts of the Great Salt Lake Region for at least 10,000 to 12,000 years. Studies of these early inhabitants are relatively new and are expected to be extended after the present war is over and materials and men are available for pursuing this research. "Early man in the Great Salt Lake Area," is the title of a paper by ELMER R. SMITH, published in the Bulletin of the Mineralogical Society of Utah,[v. 3, No. 2, 1942], in which he presents the material thus far available. He includes a number of references to reports covering the research work of other archeologists.

U. S. Geological Survey,
Salt Lake City, Utah

(Communicated manuscript received August 30, 1945, through S. T. HARDING, Chairman of Committee on Lakes; open for discussion until July 1, 1946.)

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 60, 68, 110, 118, and 120)

NOTES

New summer hydraulic laboratory--A new hydraulic laboratory, to be known as the Rocky Mountain Hydraulic Laboratory, has been established by a nonprofit corporation organized under the laws of the State of Colorado. The location is about 25 miles northwest of Boulder, Colorado, and ten miles south of Estes Park on St. Vrain Creek. The creek has a fall of about 80 feet in its quarter-mile flow across the 20-acre site.

The plan is to develop the site especially as a summer laboratory for the use of teachers, students, and others during summer vacations. Facilities are to be open to all qualified persons upon registration and payment of fees. As the climate is such as to require little housing, and as the flow and head are ample for most work, thus requiring no storage or pumping, it is expected that the charges can be kept low. Hotel and cabin accomodations are available within walking distance. Gerard H. Matthes has been named President of the Corporation; Ralph W. Powell of Ohio State University has been named Secretary; and C. J. Posey of the State University of Iowa has been named Director and Treasurer. Others instrumental in establishing the Corporation are J. C. Stevens, Francis M. Dawson, Ivan E. Houk, Adolph F. Meyer, Royce J. Tipton, Edward Soucek, Sherman M. Woodward, John L. Savage, Hardy Cross, and Clifford H. Stone.

Endowment for the study of the atmosphere--The Trustees of the estate of the late William Napier Shaw, who was Director of the British Meteorological Office, have given his meteorological library to Cambridge University, together with an endowment of about $20,000 for the maintenance of the library and for the study of the atmosphere.

Conference on hydraulics to be held at Iowa City--Plans are being made by the Iowa Institute of Hydraulic Research, State University of Iowa, for the Third Conference on Hydraulics. The dates set are June 17, 18, and 19, 1946. Inquiries concerning the Conference should be addressed to the Institute. The First Conference was held in 1939 and the Second in 1942. It is planned to hold them triennially in the future.

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Transactions, American Geophysical Union Volume 27, Number I February 1946

ANNUAL TEMPERATURE-CYCLE OF LAKE MICHIGAN

Phil E. Church

Abstract

Between November, 1941, and February, 1944, no fewer than 110 crossings of Lake Michigan were completed, on which about 2,000 bathythermograph soundings and innumerable meteorological observations were made. Eighty of the crossings were between Milwaukee, Wisconsin, and Muskegon, Michigan, at intervals averaging about ten days. The other crossings were made to the north or west of Frankfort, Michigan.

Lake Michigan essentially consists of two basins, the southern basin being nearly circular with a maximum depth of 172 meters. The north basin occupies the northern two-thirds of the lake proper, is long and narrow, and has a maximum depth of 282 meters. At the speed of the vessels from which the soundings were made, the bathythermograph, recording temperatures continuously, would descend vertically not more than 105 meters. Soundings to the bottom could be taken virtually all the way across the lake between Milwaukee and Muskegon.

The minimum temperature is reached between the middle and end of March when the main body of the lake is vertically isothermal. Its average temperature on March 15, 1942, was 2.5°C. and on March 23, 1943, it was 0.5°C. At mid-lake where the depth is 77 meters, almost the average depth of the lake between Milwaukee and Muskegon, a column one square centimeter in area in 1942 contained 19,200 gram calories, using a 0°C. base. In 1943 at the same point there were only 3,800 gram calories. Around the rim of the lake at that time there was a deep band of colder water with the center being slightly warmer. This indicates counterclockwise circulation, because the cooler and, therefore, less dense water is around the rim of the lake.

The temperature increase is slow despite the late date of the attainment of the minimum temperature. This is because the whole lake from top to bottom must heat up to a temperature above 4°C. before stratification at the surface can take place. Between Milwaukee and Muskegon the temperature reached that of maximum density in mid-May in 1942 and mid-June in 1943. In the deep basin at the north end this temperature is reached about a month later. During the entire period when the lake is warming but the temperature is below 4°C., the lake is convectively turning over.

When the lake is vertically isothermal at a temperature between 4.2°C. and 4.5°C., stratification of the water at the surface begins, and the temperature rapidly increases until mid-July or the first of August. At that time temperatures of 22°C. are observed over the southern basin and 18°C. over the northern basin. Water below the thermocline never reaches a temperature of 5°C. because of the great degree of stability of the water at the surface. The slope of the isotherms between 15°C. and 5°C. is such that there is indication of counterclockwise rotation with the stronger current northbound along the east side; again the less dense water is around the rim of the lake. When the surface has reached the above mentioned temperatures, no further surface increase takes place.

From mid-July to mid-September there is little change of surface temperature, but a small increase in the total heat-content of the lake continues, by reason of the deepening of the surface homogeneous layer. The maximum heat-content of a column one square centimeter in cross-section at the mid-lake station in 1942 was 71,600 gram calories on September 3, and in 1943 it was 66,700 gram calories again on September 3. The homogeneous layer at the surface at that time may be more than 20 meters deep on the east side of the lake and might contain well over one-half of the total heat of the lake. On numerous occasions with strong west winds, remarkable temperature decreases owing to up-welling have been observed along the west side.

The summer stationary period usually ends abruptly with the first big storm in September, and cooling takes place at a rapid rate. The heat loss may then be as much as 800 gram calories per day. The surface homogeneous layer increases in depth as cooling progresses, and strong autumn winds are able to stir deeper in this layer. Between mid-September and the first of December, when

the lake has an average temperature of about 5.5°C., the total loss in heat from the mid-lake station is very nearly 30,000 gram calories, or an average loss of about 400 gram calories per day. When a temperature of about 5.5°C. is reached, the vertical stability is so greatly reduced that a late autumn storm stirs the lake to an isothermal condition. Concomitantly the water at the bottom rises in temperature abruptly to that at the surface, and the convective turn-over period is initiated. Just prior to this time the warm belts on both the east and the west sides of the lake are most clearly defined.

When the lake becomes vertically isothermal the decrease of temperature is greatly retarded, though the number of calories lost per day is still large. On about the first of January the temperature of maximum density for fresh water has been reached and convective over-turn ceases. From about January 1 until the minimum temperature in mid-March, vertical stirring is occasioned only by strong winds which are frequent at this time of the year. By early February the water close to the shores has reached the freezing point and ice begins to form. By the first of March the winter circulation pattern is well established, with the colder water being around the periphery of the lake.

This project was jointly sponsored by the Institute of Meteorology of the University of Chicago and the Woods Hole Oceanographic Institution for the first two years and is currently being carried on by the Department of Meteorology of the University of Chicago. The complete report on this work is covered in Miscellaneous Reports in Meteorology, Numbers 4 and 18, of the University of Chicago.

University of Washington,
Seattle, Washington

(Abstract received May 16, 1945; presented at the Twenty-Sixth Annual Meeting, Washington, D. C., May 31, 1945.)

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 60, 68, 107, 118, and 120)

PERSONALIA

Herbert S. Riesbol, who has served as a Captain in the Corps of Engineers during the War, has returned to reserve status and has been appointed Acting Head, Design Flood Section, Division of Hydrology in the United States Bureau of Reclamation. His headquarters will be in Denver, Colorado.

Paul Schureman, Principal Mathematician of the United States Coast and Geodetic Survey, retired on June 30, 1945, after 42 years of service. For the past eight years he was Chief, Section of Research of the Division of Tides and Currents, while prior to that he was Chief of the Section of Tides.

S. S. Schworm, formerly in charge of the station of the United States Weather Bureau at Parkersburg, West Virginia, has been transferred to the office at Richmond, Virginia, where he is now in charge.

Clarence H. Swick retired from the United States Coast and Geodetic Survey on December 31, 1945. He entered the Survey on July 1, 1907, and after an assignment in the field, entered the Division of Geodesy as a geodetic mathematician. He became Chief of the Section of Gravity and Astronomy in 1924, and Chief of the Section of Triangulation in 1942, which position he held at the time of his retirement. He was very active in engineering and scientific societies, being a member of the American Geophysical Union, Washington Society of Engineers, Washington Academy of Sciences, Society of Sigma Xi, American Astronomical Society, and other organizations. He served as Secretary of the Section of Geodesy in the American Geophysical Union from 1931 to 1937, and President of the Section from 1938 to 1941. He has also served as Chairman of the Committee on Budget, and the Special Committee on Surveys and Maps.

F. A. Vening Meinesz, Director of the Meteorologic-Oceanographic-Geophysic Institute at DeBilt, The Netherlands, who is in this country renewing scientific contacts, has been presented with the Penrose Medal of the Geological Society of America. He is the sixteenth recipient of the Medal.

Herbert D. Vogel, Colonel, United States Army, has returned from war service and is now Division Engineer of the Buffalo Division of the Corps of Engineers.

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THE USE OF MICROSEISMS IN HURRICANE DETECTION

(Progress-report based on a report of the Navy Department released November 15, 1945,
with additional remarks by H. T. Orville, Captain, U. S. N., and by B. Gutenberg,
California Institute of Technology)

At the outbreak of the war, the collection, correlation, and administration of the Hurricane Weather Service was in the hands of the United States Weather Bureau, assisted by weather-reports as practicable from the Army Air Forces and the United States Navy. However, the Hurricane Weather Service felt keenly the lack of usual weather-reports because wartime-restrictions, with radio silence on ships, and with ships proceeding in convoys rather than at random over the ocean, had deprived weather-forecasters of weather reports over vast ocean-areas which were normally obtained from merchant-ships and other sources.

The absence of these reports from ships at sea had left unreported vast expanses of ocean where destructive storms might easily form and attain dangerous proportion. Thus, wartime-demands for accurate aerological data over these vast expanses created a problem of major proportions for the Armed Forces and the United States Weather Bureau. The Joint Meteorological Committee, a working sub-committee for the Joint Chiefs of Staff, considered the problem.

Some evidence of the use of microseisms by European scientists existed in their correlation with intense atmospheric storms. As early as 1909, reports of some application in this field was published at Apia [see 1 of "References" at end of report]. W. C. REPETTI believed that a correlation existed between microseisms recorded on the seismographs in Manila and intense storms. There also was evidence of attempts at correlation of seismograph-readings and storms in India.

A study of microseisms was made at the St. Louis University [1] during the last half of 1938 where specially designed seismographs were used. With this special arrangement it was possible to determine the direction of the incoming microseismic waves. In several instances directions were secured and these directions often pointed toward a deep low-pressure area. The hurricane of September, 1938, which passed along the East Coast caused very large microseisms from which bearings were obtained for three days. As the hurricane gradually moved upward along the coast, the bearings, as obtained, shifted with the passage of the storm. As a result of this short research-period, it was tentatively concluded that a direct relationship exists between microseisms and barometric low-pressure areas.

Similar investigations had been made in Göttingen, Germany [2] where up to four stations, with distances between 3-1/2 and 6-1/2 km were used. There, too, the microseisms seemed to radiate from low-pressure areas.

As a result of the findings at the St. Louis University, the Naval Aerological Service under the guidance of H. T. ORVILLE, Captain, U. S. N., became interested, during the early part of the War, in microseisms and their relation to severe atmospheric storms, such as hurricanes. It was visualized that the seismograph could provide methods whereby the path of destructive hurricanes could be followed from day to day even though the centers were several thousand miles away. This was a tremendously significant possibility.

Thus, after due consideration of the problem, outlined above, the Joint Meteorological Committee recommended and it was decided that the Navy would pursue this method of attack, and keep the Joint Meteorological Committee, which is composed of Army, Navy, and Weather Bureau representatives, informed of results.

Thereafter, the Navy organized a program which combined three methods for bridging the gap in the need for weather-reports from vital operational areas associated with hurricane-tracks. The first was the use of weather-reconnaissance squadrons of multi-engined aircraft designed to search out storm-centers (see Fig. 1); the second was the utilization of radar for the detection of storm

centers (see Fig. 2); the third was an aggressive research-program designed to evaluate microseismic activity in the location of severe atmospheric storms (see Figs. 3 and 4). Thus, the United States Navy commenced what is to be the first practical application of the use of seismology in the tracking of severe atmospheric storms.

Accordingly, to implement the microseismic research, plans were formulated in 1943 for the establishment of a departmental research-project of this nature by the Navy Department at the Naval Operating Base, Guantanamo Bay, Cuba. M. H. GILMORE, Lieutenant Commander, U. S. N. R., a seismologist with considerable practical experience in the field of petroleum-discovery through the use of the seismograph, was designated as Officer in Charge of the project. In this capacity, GILMORE visited instrument-manufacturers, arranged contracts for procurement of equipment, and in early 1944 supervised the installation of the first naval hurricane microseismic equipment at Guantanamo Bay, Cuba. This microseismic station consisted of three microseismic vaults equipped with special microseismic equipment designed specifically for use in hurricane-detection.

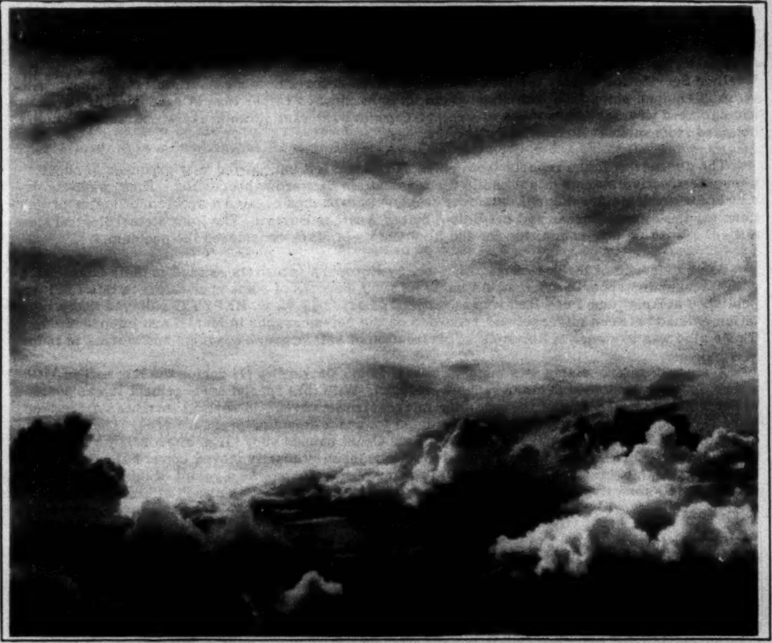


Fig. 1--Eye of a hurricane as it appeared from an airplane

The tripartite station, as this type of installation is called, has the vaults situated in a triangular pattern. Thus, a microseismic wave originating from some distant source and traveling along the Earth's surface would reach one of the corners of the triangle first, and the other two corners subsequently. By measuring the time-interval between the arrival of this microseismic wave at the three microseismic vaults, the direction of the source can be found, and in addition the amplitude or magnitude of the wave can be measured. Several excellent examples occurred during the 1944 hurricane-season. Data were collected and evaluated by Lieutenant Commander GILMORE and his

staff of enlisted assistants. The data indicated a high degree of correlation between microseismic activity and intense atmospheric storms, and in addition indicated that the origin of these microseismic waves could be determined. However, inasmuch as the project only contained one tripartite station, these results were considered highly significant but inconclusive, since triangulation of bearings were needed for accurate centering of storms.

At a conference in Washington, D. C. in late 1944, where the project was discussed in detail, it was concluded that the limitations of a one-station project made it desirable that two additional stations should be added for the 1945 season. These stations were to be located at Naval Operating Base, San Juan, Puerto Rico, and Naval Air Station, Richmond, Florida. The addition of these stations would permit a check by triangulation on the origin of microseismic waves. It was felt that this would establish conclusively the merits of such an investigation. The recommendation for the addition of these two stations was made by F. A. DAVIDSON, Captain, U. S. N., of the Navy's Hurricane Weather Central in Miami, Florida, who took a very keen interest in the project, and materially assisted with the work during the 1944 season by evaluating the results from an aerological viewpoint.

Fig. 2--Eye of a hurricane and precipitation area as observed on the radar-scope

Lieutenant Commander GILMORE again was responsible for obtaining instruments for the outfitting of the additional stations. Equipment was procured, a training program established for additional necessary personnel, and installations completed by the summer of 1945, at which time everything was in readiness for the hurricane-season. To facilitate the administration of the project and to place operational control near the scene of the project, the entire program was placed under the cognizance of the Commander, Gulf Sea Frontier, W. S. ANDERSON, Vice Admiral, U. S. N. WILLIAM LOVELAND, Commander, U. S. N., the aerological officer on the staff of the

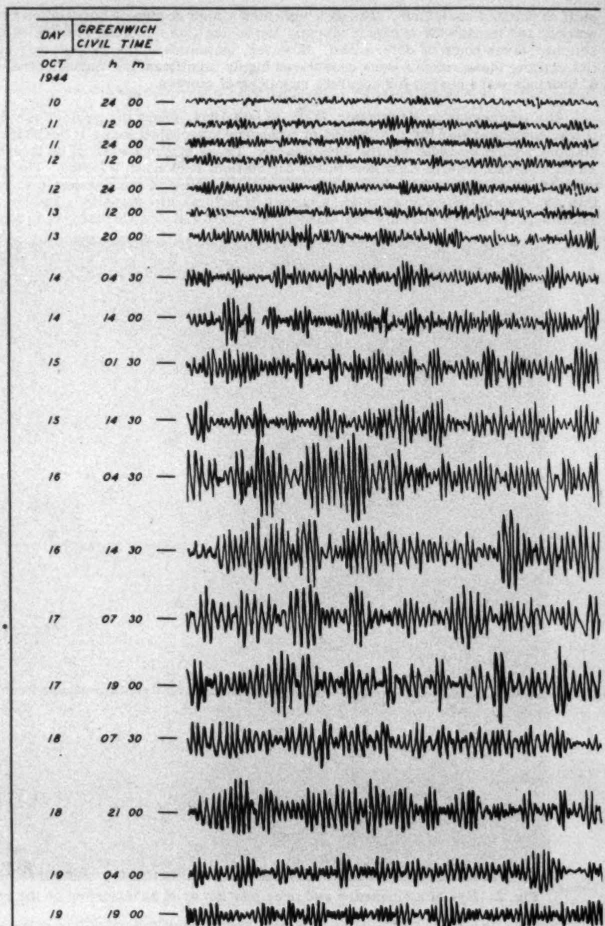
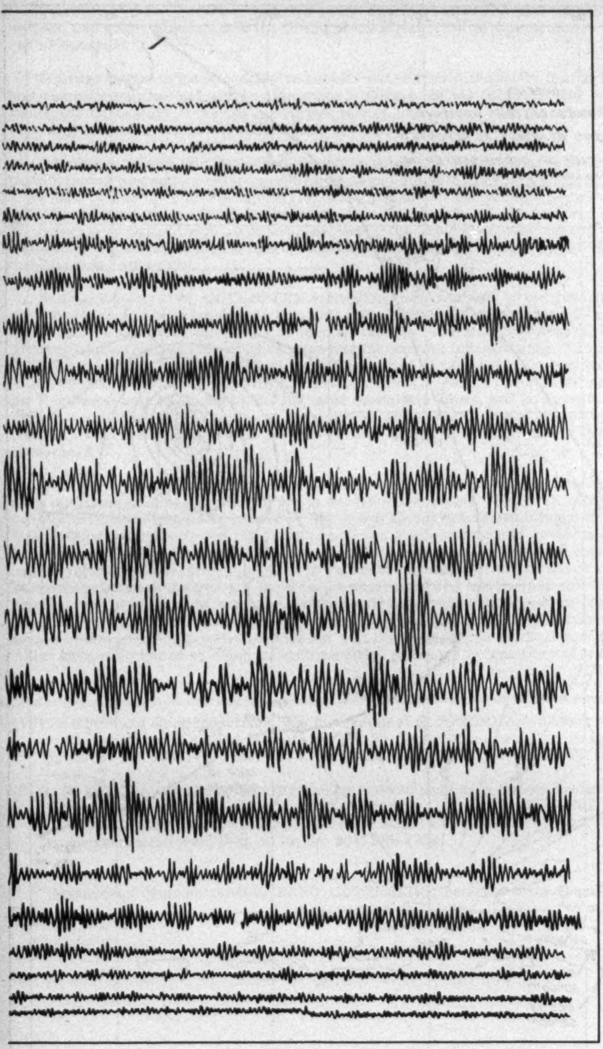
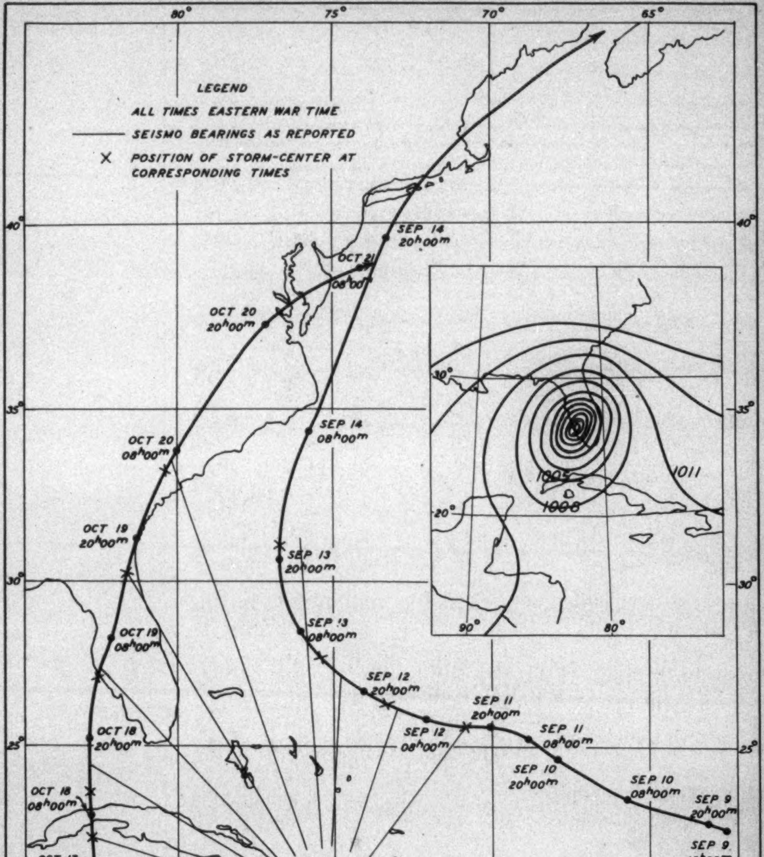


Fig. 3-- Amplitudes of microseisms for selected 15 minute intervals during



passage of the hurricane of October, 1944, recorded at Guantanamo Bay


LEGEND
ALL TIMES EASTERN WAR TIME
SEISMO BEARINGS AS REPORTED
X POSITION OF STORM-CENTER AT CORRESPONDING TIMES
80°
75°
70°
65°
40°
35°
30°
25°
20°
SEP 14 20h00m
OCT 21 08h00m
OCT 20 20h00m
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OCT 18 08h00m
OCT 17 20h00m
OCT 16 20h00m
OCT 15 20h00m
OCT 17 08h00m
OCT 15 08h00m
GUANTANAMO BAY
OCT 16 08h00m
OCT 13 20h00m
OCT 14 20h00m
OCT 13 08h00m
OCT 14 08h00m
1011
1005
1008
90°
80°

Fig. 4-- Tracks of hurricanes, September 9-15, 1944, and October 13-21, 1944. (Inset) Isobars of October hurricane on entry into Florida

Commander, Gulf Sea Frontier, assisted in the administrative and operational supervision of the project, and materially assisted the Office of the Chief of Naval Operations in the implementation of this program.

In order to obtain more conclusive results and to establish finally if a correlation did exist between microseisms and severe atmospheric storms, BENO GUTENBERG, in charge of the Seismological Laboratory of the California Institute of Technology, was placed under contract by the Navy Department as technical adviser and consultant for the 1945 season.

In connection with this project, it should be noted that expenses have been relatively small; the installation of a complete seismograph-vault, complete with instrument, costs in the neighborhood of $8,000. Thus, the entire program, including equipment and personnel, has cost approximately $75,000. When compared with the property-damage that intense atmospheric storms can cause, this expense is insignificant. For example, the great September hurricane of 1938 which lashed the Eastern Seaboard caused property damage in the neighborhood of $300,000,000, not to mention considerable loss in life.

During August, 1945, GUTENBERG visited the microseismic project for the purpose of studying data which had been compiled. He said, "The studies which I have made here thus far leave no doubt that the data from microseisms furnish valuable information for the forecasting of hurricanes. The correlation between the microseisms and the storms is convincing." In a later report dated September 6, 1945, GUTENBERG stated, "The writer of the present report has suggested the use of microseisms for the forecasting of storms for many years. The results which he has seen in the Caribbean area exceeded by far his most optimistic hopes, and he is certain that the use of microseismic data in the Caribbean area,as well as in other regions,for the location of hurricanes and the preparation of advisories will aid greatly in reducing the losses of life and damage from hurricanes."

The above conclusions serve to substantiate the faith of the United States Navy in the usefulness of microseisms as a valuable aid in weather-forecasting. However, although the preliminary results have been optimistic in nature, the research-project as established by the Navy Department was to show conclusively the relationship between microseisms and severe atmospheric storms. At this time the data for the 1945 hurricane-season are not complete, and consequently the results are as yet considered inconclusive. It is expected that once all the evidence is assembled, a good correlation between the two will have been established, and this method will become a valuable practicable aid to locating, tracking, and forecasting movements of severe tropical storms, thereby effectively contributing to the minimizing of loss of life and property-damage. This will serve as a supplementary support and aid to, but will not replace, the aircraft-reconnaissance squadrons, which have contributed so much to wartime Naval Aerology in locating and tracking hurricanes.

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[1] For literature on microseisms, see for example: E. RAMIREZ, An experimental investigation of the nature and origin of microseisms at St. Louis, Missouri, Bull. Seis. Soc. Amer., v. 30, pp. 35-84 and 139-178, 1940, and L. M. MURPHY, Winter microseisms, pp. 19-26, of this issue.

[2] H. D. KRUG, Ausbreitung der natürlichen Bodenunruhe nach Aufzeichnungen mit transportablen Horizontalseismographen, Zeits. für Geophysik, v. 13, pp. 328-348, 1937.
F. TROMMSDORF, Untersuchungen über die natürliche Bodenunruhe mit transportablen Dreikomponentenstationen, ibid, v. 15, pp. 304-330, 1939.

(Manuscript communicated by BENO GUTENBERG, received December 17, 1945; open for discussion until July 1, 1946.)

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 60, 68, 107, 110, and 120)

NOTES

Earthquakes in November and December 1945--Only light local shocks were reported felt in the United States, the more notable being in Buckingham County, Virginia, late in October; Miami Beach, Florida, on December 22; and near Lake Ossippee, New Hampshire, on December 28. Other parts of the country no doubt experienced similar shocks, but they have not yet been reported. There was apparently no seismic activity associated with the reported volcanic activity at Crater Lake, Oregon, in September, 1945.

Two important earthquakes, both submarine, occurred abroad. The shock of November 27 in the northern end of the Arabian Sea generated a seismic sea-wave which killed 4000 persons along 100 miles of coast near Karachi, India. On December 28, an earthquake of great magnitude was tentatively located between New Guinea and the Bismarck Archipelago, but no local reports on it have been received.

The following provisional epicenters were reported by the United States Coast and Geodetic Survey cooperating with the Jesuit Seismological Association, Science Service, and a selected group of widely scattered seismological stations:

Date		Time	Location		
		h m	°	°	
November	3	22 09.0	59.1 N,	151.0 W	Alaska
	8	9 05.5	81 N,	7 W	Off northern Greenland
	8	10 02.5	81 N,	7 W	Off northern Greenland
	16	18 02.5	27.7 N,	135.8 W	Felt at Juneau and Skagway, Alaska
	26	5 12.9	23 S,	180 W	Tonga Islands
	27	21 56.8	22 N,	62 E	Arabian Sea
December	8	1 04.0	1 S,	148 E	Northeast of New Guinea
	9	20 45.6	15.0 N,	92.0 W	Guatemala
	23	8 09.4	10.2 N,	61.7 W	Felt at Pedernales, Venezuela, on Orinoco Delta
	27	4 41.0	5.5 S,	149 E	New Guinea
	28	17 48.4	5 S,	147 E	New Guinea

Volcanic activity on Umnak Island in the Aleutians--Late in May, 1945, mild earthquakes marked the beginning of a rather spectacular eruption on Umnak Island, 70 miles southwest of Dutch Harbor and about 35 miles south of Bogoslof Island, the notoriously unstable island of the Aleutian chain. The northeastern half of Umnak Island is occupied by an unnamed caldera--perhaps the second largest in North America--6-1/2 to 7-1/2 miles across and 100 to 200 feet deep from rim to floor. The first week in June, one of about a dozen cones on the floor of the caldera erupted violently. The early eruptions blew steam and ashes several thousand feet high and several inches of ash was deposited on the southwest outer slopes of the caldera. By June 10, the pre-existing crater had been enlarged to a diameter of about 100 yards and the cone had been increased in height possibly 150 feet by bombs and lapilli. During the early stages, basaltic lava issued from a fissure at the southwest base of the cone, forming a flow which at the end of August was more than four miles long. The explosive activity declined somewhat in the last half of June, but increased again in early July. During August activity consisted mainly of quiet exhalation of steam.

G. D. Robinson, and later, Howel Williams, both of the United States Geological Survey, visited the volcano for a few days in June at the request of the Army, and W. E. Wrather and John C. Reed of the Survey, visited it in August. Ray E. Wilcox, of the Signal Corps, who worked on the Gardiner River Complex in Yellowstone National Park, has kept track of the eruptions insofar as his other duties permitted. He reports that after a period of quiescence, renewed explosive activity was observed about December 3, and by the twelfth, a new lava flow had made considerable progress.

The recent activity, the latest of many historically recorded eruptions in the Aleutian Islands and the Alaska Peninsula, emphasizes the need for volcano-research in this important, but little known, portion of the Circum-Pacific Ring of Fire.

Transactions, American Geophysical Union Volume 27, Number I February 1946

NOTES ON ACTIVITY OF PARÍCUTIN VOLCANO DURING DECEMBER, 1945

Konrad Krauskopf

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Department of the Interior.)

The Volcano continued quiet during the first week of December, but thereafter was fairly active. The eruption-cloud was white to light gray, fairly narrow, rising in cauliflower puffs to a height of 300-400 meters above the crater, then spreading horizontally in a long dust-plume, usually northeastward. Considerable noise accompanied emission of the cloud, and showers of small incandescent stones were fairly continuous. Because the angle of the vent was slightly inclined much of the time, many of the stones fell on the flanks of the cone, especially on the southeast. The eruptions became gradually quieter toward the end of the month.

The renewed activity brought about slight changes in the form of the crater. The two vents noted late in November persisted, but activity from the south vent was limited largely to quiet emission of gas. The position of the north vent moved until it was practically in the center of the crater, and a small cone was built up around it. The striking pattern of concentric faults and steam-cracks developed during the quiescent period of late November and early December was obliterated with the start of stronger eruptions, but faults were beginning to develop again in late December.

Activity at the lava bocas changed greatly. Flows from the southern boca-ridge (along a radial fissure) gradually weakened and ceased to move about the middle of the month. Along with this change came an increase in the amount of lava from the northern ridge (along a fissure parallel to the base of the cone). For most of the month the flow from this ridge was fed by two bocas, lava from one of them moving for a time with a rate of a meter per second. Near the end of the month these two bocas became inactive and a third took their place as a feeder for the flow, but so far the amount of lava from this new boca seems considerably less than that from the other two. Along the fissure on the northern boca ridge several "domes" of viscous lava rose gradually during the month to form an almost continuous wall three to five meters high.

The small lava-flow extending southwest from the southern boca-ridge ceased to move about the middle of the month. The long flow from this same ridge which lies against the hills to the west continued to move long after its feeding boca became stagnant, although the movement resulted in a piling up of lava rather than further advance of the lower end. The flow from the northern boca ridge advanced steadily during the month along a wide front, completely obliterating the last remnants of the village of Parícutin, and at the very end of the month it reached the edge of the long flow of last year which joined the San Juan flow west of the town.

U. S. Geological Survey,
Washington, D. C.

(Communicated manuscript received January 10, 1946)

NOTES AND PERSONALIA

(See also pp. 14, 48, 59, 60, 68, 107, 110, and 118)

NOTES

Volcanic activity at Crater Lake--There are no further reports of volcanic activity at Crater Lake, Oregon. Unusually bad weather and heavy storms have prevented F. W. Cater, Jr., of the United States Geological Survey, from reaching the rim to observe what might be going on.

The Military Geology Unit of the United States Geological Survey--The Military Geology Unit of the United States Geological Survey has shifted the main emphasis of its work somewhat from strategic military problems to investigations of broader economic scope. Some of the strictly military phases of the work are being concluded, and geologists and other specialists of the Unit are now working with the Natural Resources Section of the Supreme Commander of the Allied Powers, in an economic survey of Japan and Korea. T. A. Hendricks is in charge of the field work of the Unit with headquarters in Tokyo. Harry S. Ladd went to the Pacific late in November to help in organizing the work, and was expected to return soon after this issue of the Transactions went to press. Although the regular term of overseas duty is six months, the program is expected to last somewhat longer, and those who so desire may stay longer.

Correspondence should be addressed in care of the Natural Resources Section, G.H.Q., S.C.A.P., Advance Echelon, A.P.O. 500, c/o Postmaster, San Francisco, California.

Members of the Unit now overseas are as follows:

Esther J. Aberdeen
Thomas G. Andrews
Morris E. Austin
Raymond Becker
Francis Bell
Frederick Blach
Victor R. Boswell
Kirk V. Cammack
J. David Cerkel
Charles W. Chesterman
Alfred H. Chidester
John J. Collins
Dorothy Faulconer
David Gallagher
Allan B. Griggs
G. Richards Gwynne
Thomas A. Hendricks
Lowell S. Hilpert
Morris A. Huberman
Arthur Jenke
Charles Johnson
Harry S. Ladd
Wolf Ladijinsky
Frederic Main
W. T. Reid
John Rodgers
Samuel C. Salmon
Raymond D. Sample
Edward Sampson
Robert J. Seidl
Philip Stephenson
Rollin Stevens
William S. Swingler
Arvi O. Waananen
Clyde Wahrhaftig
Frank Whitmore
Melvin R. Williams

Arctic Institute of North America--The Arctic Institute of North America has opened offices on the campus of McGill University in Montreal, under the direction of A. L. Washburn. Considerable progress is being made in carrying out their program. The Institute is a private organization, but is organized on an international basis, for research in Alaska, Canada, Newfoundland, Labrador, and Greenland, which are all represented on the Board of Governors. It is incorporated in the State of New York, and steps are under way for incorporation in Canada. The purposes and objects of the Institute, as set forth by its Constitution, are:

(a) To initiate, encourage, support and advance, by financial grants or otherwise, the objective study of Arctic conditions and problems, including such as pertain to the natural sciences, sciences generally, and communication.
(b) To collect, arrange, and preserve records and material relating to the Arctic regions and especially to such areas thereof as form part of, or are contiguous to, the continent of North America.
(c) To make such records and material available for pure and applied scientific use by properly qualified individuals and organizations, including governmental agencies.
(d) To arrange for, or to assist in the publication of reports, maps, charts, and other documentary material relating to the Arctic regions.
(e) To establish and maintain close contact with other Arctic institutes and organizations engaged in similar or related fields of study.

Corrigendum--Advice has been received of a number of omissions and corrections relating to Table 1 in the paper "Education in Geophysics" [Trans. Amer. Geophys. Union, v. 26, No. 3, pp. 463-476, December 1945]. A member of the faculty at Columbia University advises that Meteorology is taught as a graduate course, as well as an undergraduate one, as now shown. Data have now been received relating to geophysical education at the University of Chicago which indicate that instruction is given in all of the branches of Geophysics listed in the Table. Word concerning other corrections and omissions is invited, and in a subsequent number a table of the corrections and the additional data will be published.

Transactions, American Geophysical Union Volume 27, Number I February 1946

REPORT OF COMMITTEE ON RUNOFF--1944-1945

R. W. Davenport, Chairman

W. C. Ackermann
Bertram Barnes
Merrill Bernard
Bruce R. Colby
Howard L. Cook
E. S. Cullings
G. A. Hathaway
W. G. Hoyt
C. R. Hursh
Carl F. Izzard
Karl Jetter
Phillip Light
Norbert H. Leupold
Charles C. McDonald
F. T. Mavis
C. E. Ramser
L. K. Sherman
Waldo E. Smith
F. F. Snyder
H. G. Wilm

The membership of the committee has been selected to afford good representation of geographic sections and of organizations engaged in runoff research. Some new members were added during the year in order to strengthen the representation of the committee in certain phases of runoff research. NORBERT H. LEUPOLD submitted his resignation in April because his work is no longer directly related to runoff-research.

At the beginning of the year members of the committee met to discuss its setup and plans for the future. The committee has two subcommittees, one dealing with floods and the other with subsurface-flow. The question was considered whether progress might be facilitated by the addition of one or more additional committees dealing with logical classifications of the subject of runoff. The confusion in nomenclature and terminology relating to runoff was discussed,but it was thought that the present time was not fitting for comprehensive consideration of standardization. It was considered important that the writer of a paper dealing with runoff should make clear the usage of terms he follows in his paper. It was emphasized that there is still an important need for better understanding or liaison between groups dealing with the influence of land use on stream-flow and those dealing with control and development of streams.

The reports of the subcommittees on floods and subsurface-flow are attached as appendices A and B, respectively.

C. E. RAMSER (United States Soil Conservation Service, Washington, D. C.)--An effort has been made by the Soil Conservation Service to continue the collection and compilation of hydrologic data on nearly all of its field projects,in spite of the loss of many of its key men engaged in hydrologic activities. Analysis of data has been confined principally to supplying field technicians with information required in the design of farm ponds and maximum rates of runoff for use in design of small conservation channels and structures. It is possible that postwar activities may be expanded by the establishment of additional field projects to obtain information needed at other locations for use in the regular field soil- and water-conservation program.

The general policy will likely be to establish any new projects on state-owned or controlled lands near the State Agricultural Experiment Stations. It is believed this will result in longer continuous records and less interference with a carefully planned cropping program.

No regular hydrologic publications were issued during the year. The following two mimeographed reports were prepared for limited distribution, principally within the Soil Conservation Service:

Preliminary report on watershed studies near Waco and Garland, Texas, by L. L. HARROLD, D. B. KRIMGOLD, and L. A. WESTBY, and

Hydrologic studies, compilation of rainfall and runoff from terraced and other areas of the Central Piedmont Soil and Water Conservation Experiment Station, Statesville, North Carolina, by L. L. HARROLD.

C. F. IZZARD (United States Public Roads Administration, Washington, D. C.)--The Public Roads Administration instituted a cooperative project with the Soil Conservation Service in 1942 for experimental investigation of the mechanics of overland flow on paved and turf-surfaces, with particular relation to the application of such research to the design of drainage facilities for flight strips. Experimental work utilizing rainfall simulators developed by the Soil Conservation Service was carried on in 1942 and 1943 and has been reported in the Transactions of the American Geophysical Union for 1943 and 1944. The experimental program has been inactive since the fall of 1943 but analysis of the data is still continuing. A progress report will probably be published in 1945. Plans for resumption of experimental work have not been formulated.

In 1944 the Highway Research Board organized a committee on surface drainage with membership from highway departments representative of the various climatic regions of the United States and, in addition, membership from various Federal agencies concerned with the flow of water through highway or similar structures. A preliminary report of this committee recognizes the need for information useful to the practicing engineer in estimating peak rates of runoff from small drainage areas. A number of state highway departments are now attempting to apply rational methods for the hydraulic design of culverts and bridges. The committee recommends the integration of data on runoff from small drainage areas in order that the practicing engineer may benefit by the vast amount of experimental measurements which have been accumulated in the past ten years. The committee also recommends further experimental research to fill in the gaps in our knowledge on the flow of water through culverts and similar structures, including storm sewers and their appurtenances.

MERRILL BERNARD (United States Weather Bureau, Washington, D. C.)--The Weather Bureau has extended its seasonal forecasting of water supply in the Columbia Basin through statistical procedures relating to precipitation and stream-flow. The forecasts of seasonal runoff from important streams in the Basin are made progressively beginning October 1, in terms of the minimum possible, probable minimum, most probable, probable maximum, and maximum possible. The issuance of periodic bulletins giving the results of these forecasts was begun during the past winter. Combinations of observed precipitation data with 30-year normals for the remaining months of the season make it possible to provide the irrigation and utilities interests with forecasts of water supply well in advance of the operation season. The technique used is described in a paper, "Forecasting seasonal runoff by statistical methods," by LIGHT and KOHLER, published in the Transactions of the American Geophysical Union, pp. 719-735, 1943.

R. W. DAVENPORT (United States Geological Survey, Washington, D. C.)--The program of the Geological Survey for systematic and continuous measurement of runoff has two principal objectives: first, to provide information for the design of future works; and second, to provide information for efficient current operation and use of available water. In serving the second purpose, the Survey makes current stream-flow information available to water users locally and on a national scale through the Water Resources Review. Collaboration with the corresponding Canadian agency, the Dominion Water and Power Bureau, extends the coverage to Canada. As a further aid to efficient operation of water facilities, a program of furnishing outlooks as to prospective runoff during the ensuing month has been continued in several states. These outlooks are based on analyses of stream-flow records and an evaluation of the influence of antecedent factors on subsequent runoff. Actual runoff is dependent on future events as well; therefore, statements are prepared giving (1) the lowest possible runoff under existing hydrologic conditions, and (2) prospective runoff, provided weather conditions during the period of outlook are normal.

Another activity of the Geological Survey of current interest relates to the investigation of water-supplies for stock-ponds or tanks, as the western ranchers call them.

Small stock-water ponds, artificially constructed by impounding the runoff from a "dry wash," provide means for maintaining stock on the arid rangelands and so permit the harvesting of a valuable crop. To the hydrologist these tanks suggest a means for obtaining information on the infrequent and scant runoff from small semiarid drainages, and on rates of evaporation from small ponds. Such information can equip the grazier with quantitative data for the economic development and operation of surface-water facilities on the public range.

To this end the Geological Survey, under sponsorship of the Office of Land Utilization of the Department of the Interior, has begun a program to collect systematic records of the rise and fall of the water surface in several representative stock-ponds. Staff gages have been installed on a few representative tanks in Arizona and New Mexico, and provision has been made for regular readings. The reservoirs range in size from two to 200-acre-feet and rarely overflow, so that a staff-gage record, together with a capacity survey properly interpreted, will enable the derivation of the volume and frequency of recharge, and during the long periods between recharge, depletion rates are indicative of seepage and evaporation.

Emphasis will be placed on obtaining wide areal distribution and sampling of runoff from small areas.

Two members of the Committee, G. A. HATHAWAY and F. F. SNYDER, have participated in an important application of hydrologic techniques to the war. This activity, as described in a recent release of the Office of the Chief of Engineers, related to the organization of a flood prediction service along the Rhine for the benefit of the recent extensive military campaign. The service provided general river-stage predictions and reports on icing and flooding conditions for the Rhine River and its tributaries downstream from the Swiss border. The work was carried on by civilian specialists of the Office of the Chief of Engineers and other Federal agencies in cooperation with Army personnel. Mr. HATHAWAY, as Head Engineer of the Reservoir Operation and Hydrology Section Civil Works Division, Office of the Chief of Engineers, is credited with setting up this flood prediction service. Mr. Snyder has also had an important part in the project.

The reports of Committee members indicate generally that research activities have been h much curtailed during the past year, doubtless because of direct and indirect effects of the War. Reports of the two subcommittees are given in Appendices A and B, below.

U. S. Geological Survey,
Washington, D. C.

(Manuscript received July 26, 1945; open for discussion until July 1, 1946.)

APPENDIX A--REPORT OF THE SUBCOMMITTEE ON FLOODS

Gail A. Hathaway, Chairman

F. F. Snyder B. R. Colby Phillip Light Waldo E. Smith

Steps were first taken to organize this subcommittee in August, 1943. The committee members shown above were appointed subsequent to the Annual Meeting in April, 1944.

The war activities of the committee members have prevented any organized work by the subcommittee in the last year. As soon as conditions permit, the subcommittee has in mind an initial program involving a review of our present knowledge of the unit-hydrograph with a view to developing its limitations, deriving procedures for correlation, and standardizing wherever possible on methods of analysis and application.

Office, Chief of Engineers,
War Department,
Washington, D. C.

(Manuscript received July 26, 1945; open for discussion until July 1, 1946.)

APPENDIX B--REPORT OF THE SUBCOMMITTEE ON SUBSURFACE FLOW

C. R. Hursh, Chairman

Because of war programs, no attempt has been made to expand the membership or the activities of this subcommittee during the past year. A statement of research-needs, to comprehend subsurface stormflow better, was presented at the last Annual Meeting and appears in Part V, Transactions of 1944, pages 743-746.

Exchange of correspondence has brought to light a growing interest in the phenomena of dynamic subsurface water-movements during storm periods. During the year a valuable paper by PARSONS [see 1 of "References" at end of report] has emphasized the importance of interpreting the flood hydrographs in terms of "the various elements of basin storage" which he recognizes as outflows from surface, subsurface, and ground-water storage. Following the general method of BARNES [2], he has presented a graphical recession analysis indicating that storm runoff appears as three approximately straight lines when plotted on semilogarithmic paper--representing the surface, the subsurface, and the ground-water fractions. This concept is then used in the calculation of flood hydrographs from precipitation records. STAFFORD and TROXELL [3] have likewise recognized runoff as being of three types: (a) surface storm-runoff; (b) subsurface storm-runoff; and (c) ground-water seepage, and have associated these three types with basin characteristics in the San Bernardino and Eastern San Gabriel mountain drainages in southern California.

For the southern Appalachian mountain region ACKERMANN [4] has also found that for small watersheds (100 acres), "The surface-flow was completely gone in about three hours, which permitted the subsurface-flow to appear as a distinct, rounded, secondary peak." ACKERMANN, however, rightly raises the point that, "Despite agreement with what other investigators have found and named subsurface-flow, I feel that our analyses, like the others, lack physical definiteness. For example, how can we be sure that this third flow component is subsurface-flow and not ground-water flow from a portion of the area which is particularly pervious. Perhaps the answer lies in more observational hydrology."

Certainly it is obvious that additional terminology is needed to express runoff-phenomena. It is true that at present the explanation of subsurface-storm runoff cannot well be explained in terms of known physical phenomena.

Secondary rounded peaks appear in the storm-hydrograph after the recession of surface-runoff from small drainages on the Coweeta Experimental Forest which is located in the high rainfall belt of the North Carolina mountains. Field examinations of these drainages indicate the presence of deep colluvial soil-deposits at the bottoms of slopes and in ravines tributary to the main drainage-lines. As these colluvial deposits are made up largely of angular rubble, they are relatively porous and may conceivably serve as aquifers for detention storage. Because they drain rapidly and are in direct contact with the surface streams, it is possible that these colluvial fills function in a manner similar to surface detention basin types of reservoirs. The possible role of talus deposits on mountain slopes on the concentration of runoff has been suggested by TROXELL [5], STAFFORD and TROXELL [3], and others [6, 7].

There is, therefore, some evidence that subsurface stormflow is a natural phenomenon associated with basin storage characteristics. It reflects a form of temporary underground detention storage in aquifers which function only during storm periods and drain more rapidly than those supplying ground-water runoff. A second logical explanation of subsurface stormflow in terms of natural physical processes has to do with the rapid seepage from porous soil banks in which water has been stored during flood stages. This subject has been mentioned in a previous report of the subcommittee.

In addition to the above two interpretations of subsurface stormflow phenomena, there are undoubtedly other basin characteristics that can give rise to subsurface stormflow, and it is hoped that these will be brought out through further discussion.

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[2] BERTRAM S. BARNES, The structure of discharge recession curves, Trans. Amer. Geophys. Union, pp. 721-725, 1939.
[3] HARLOW M. STAFFORD and HAROLD C. TROXELL, Differences in basin-characteristics as reflected by precipitation-runoff relations in San Bernardino and eastern San Gabriel mountain drainages, Trans. Amer. Geophys. Union, pp. 21-35, 1944.
[4] WILLIAM C. ACKERMANN, Committee correspondence.
[5] HAROLD C. TROXELL and others, Floods of March, 1938, in Southern California, W. S. Paper 844, U. S. Geological Survey, 1942.
[6] M. D. HOOVER and C. R. HURSH, Influence of topography and soil-depth on runoff from forest land, Trans. Amer. Geophys. Union, pp. 693-697, 1943.
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Appalachian Forest Experiment Station,
U. S. Forest Service,
Asheville, North Carolina

(Manuscript received July 16, 1945; open for discussion until July 1, 1946.)

Transactions, American Geophysical Union Volume 27, Number I February 1946

REPORT OF THE COMMITTEE ON INFILTRATION, 1944-1945

G. W. Musgrave, Chairman

The personnel of the Committee and the affiliations with the six subcommittees follow:

(1) Infiltration and the Physics of Soil Moisture and of the Infiltration Process
    B. T. Shaw (Chairman) Willard Gardner S. J. Richards F. L. Duley
(2) Infiltration in Relation to Ground-Water
    Walter N. White (Chairman) S. W. Lohman Samuel F. Turner
(3) Infiltration in Relation to Snow and Its Physical Properties
    Walter T. Wilson (Chairman) B. T. Shaw George D. Clyde
(4) Infiltration in Relation to Irrigation
    M. R. Lewis (Chairman) Harry F. Blaney Howard L. Cook
(5) Infiltration in Relation to Evapotranspiration and the Consumptive Use of Water
    Harry F. Blaney (Chairman) Walter N. White L. K. Sherman
    Colin A. Taylor José Garcia Montes
(6) Infiltration in Relation to Surface-Runoff
    Howard L. Cook (Chairman) G. A. Hathaway W. W. Horner
    R. A. Hertzler W. B. Langbein

During the past year, wartime activities demanded the attention of at least half of the members of the Committee to the exclusion of opportunities for research upon infiltration. Throughout the country as a whole, much the same situation prevailed as that within the Committee, and no attempt is being made in this report to catalogue the research of the year.

However, three of the members of the Committee are serving also on a committee of the American Society of Civil Engineers under the general chairmanship of BORIS A. BAKHMETEFF, with the assignment of preparing a section on infiltration to appear in a manual of practice in hydrology. This work is under the immediate direction of W. W. HORNER, Chairman of the Committee of Hydrology of that organization.

The Committee on Infiltration has collaborated closely with the Research Committee on Ground-Water, and during the year just past has considered various means of developing the research on these two fields. It is clearly apparent that factual information as to the effects of infiltration upon ground-water under various climatic, soil, and geologic conditions is at present most limited. Nevertheless, such information would be most useful to numerous branches of hydrology.

However, during this past year more and more attention has been given to the mechanics of the infiltration process. The Subcommittee on Physics of Soil Moisture, in particular, has given considerable thought to the matter, and has recognized the fact that even though marked advances in our basic knowledge of the physics of the process have occurred during recent years, nevertheless there is still much that is not understood.

It may be worthwhile outlining some of the items in the process that are fairly well established. When water is applied to the surface of the ground at a rate equal to or exceeding the rate of infiltration, saturation occurs in the zone near the surface of the ground. As the application of water continues, there is an advancing moisture-front primarily under the influence of the capillary-potential, that extends as far as continuous films of moisture exist. When this moisture is advancing into a dry soil, the front between the wetted zone and the dry zone is sharply defined, that is, an air-water interface exists. The moisture-content of this wetted front is approximately, or perhaps precisely, that of the field-capacity. The rate of intake at the surface meanwhile has decreased, the rate of decrease being rapid at first and later quite slow.

Between the saturated zone at the surface and the moisture-front in the soil, there is a moisture-gradient and an energy-gradient. BODMAN and COLMAN have computed the energy-gradients for various soils under laboratory-conditions, and have published a paper (Proceedings Soil Science Society of America, 1943) which is exceedingly stimulating to our thinking. Numerous trends and leads toward further research have been indicated.

WILLARD GARDNER has long given attention to problems of this kind, and the Committee is fortunate in having a paper from him. His paper indicates the need of future research in this field. It is anticipated that, as a result of further thinking and further research, there will be some tangible results forthcoming.

U. S. Soil Conservation Service,
Washington 25, D. C.

(Manuscript received October 27, 1945; presented at the Twenty-Sixth Annual Meeting, Washington, D. C., May 31, 1945; open for discussion until July 1, 1946.)

APPENDIX A--REPORT OF THE SUBCOMMITTEE ON THE PHYSICS OF THE INFILTRATION PROCESS

B. T. Shaw, Chairman

This Subcommittee was commissioned to report on the nature of the infiltration process from the standpoint of physical principles. Many excellent papers have been written describing the influence of various factors on infiltration. However, as yet, no generalization has been developed that has wide application. It would be desirable, of course, to develop an invariant relationship, if one exists, into which soil-parameters could be substituted in order to evaluate the infiltration rate under a particular set of conditions. The Subcommittee does not know that an invariant relationship exists, but in the following short paper, GARDNER points out an approach to the problem. It need not be particularly disturbing that soil permeability varies so widely with time at a particular location. If a generalization can be developed, we will then be ready to isolate the permeability-factor in the equation and study the causes of its variation.

Bureau of Plant Industry,
U. S. Department of Agriculture,
Beltsville, Maryland

INFILTRATION

Willard Gardner

Although the fundamental principles governing the movement of moisture in a soil that is saturated are concise and comprehensive, the soil through which water moves varies greatly from place to place. This introduces difficulties. Sunshine, frost, rain, snow, topography, running water, micro-organisms, and the plant-cover influence directly the development of the surface-horizons, whereas the subsoil reflects the geologic features. It is to be expected that such local characteristics as soil-permeability should vary greatly from point to point.

Infiltration-capacity, in the broad sense of the term, integrates physical conditions that vary with depth, but inasmuch as the moisture-content changes from time to time in the surface and in the subsoil, giving rise to changes in boundary-conditions, a corresponding change is to be expected in the infiltration-capacity.

If, however, water is applied to the surface of a deep dry soil that is uniform with depth, the rate at which water is taken in tends to decrease toward an asymptotic value which might well be regarded as a soil characteristic. Likewise, for field-soils that are deep, even though there is a profile-development, such an asymptotic rate should exist which might well characterize the profile. The manner in which this equilibrium-rate is approached would of course differ from profile to profile and would depend also upon the original moisture-distribution in the profile.

A sand- or gravel-subsoil that is covered with silt may have an infiltration-capacity that is essentially indifferent to the porous layer. On the other hand, water might percolate rapidly at first through a surface-layer of light sandy soil that is underlain with less permeable material. The mechanical action of the raindrop itself on soil that is denuded of vegetation might well seem to convert a profile that would otherwise be permeable to one that is resistant to infiltration. The presence of dispersed air-bubbles in the soil-moisture must have significant influence on the dynamics of the moisture through the profile.

It has been observed in the laboratory many times that if water is permitted to percolate downward in a vertical tube of dry uniform soil, it moves rapidly at first, the rate of percolation diminishing as the water-front advances, and that it takes a long while for the discontinuity in color at the water-front to disappear. This may be said also in general concerning the movement of water in any direction. The liquid "channels" at the water-front are so very small that there is required a large capillary gradient in addition to the pull of gravity to drive the water from soil-particle to soil-particle. Many of these small "channels" may consist of isolated tubes that are bounded by air-water interfaces.

The dynamics of soil-moisture has been considered essentially from the macroscopic point of view, the physics of the interface being almost entirely suppressed. The DARCY equation is concerned essentially with porous media that are saturated and contains but a single parameter that is characteristic of the media, and this is the permeability-factor or coefficient. This equation is combined with the equation of continuity for incompressible fluids thus leading to the LAPLACE equation, concerning which a vast literature exists.

Various theoretical papers have been presented from the Utah Experiment Station indicating the application of the dynamic theory to the solution of drainage-problems. The pioneering work of SLICHTER and KING at the University of Wisconsin is of particular interest and value.

The difficulties are considerably increased when we undertake to modify the DARCY equation so that it may be applied to the movement of water in soils that are not saturated, and in most problems that are of direct interest to the farmers the soil is not saturated. It was proposed at the Utah Experiment Station that the permeability-factor be made directly proportional to the moisture-content of the soil, and qualitative tests seem to indicate that this may suffice reasonably well, although it is a problem that deserves careful consideration.

It may be of interest to introduce an undetermined function of the moisture-content,

$$f = f\ (\rho)$$

as a factor in the DARCY equation, thus,

$$v = -kf\nabla\phi,$$

$\nabla\phi$ being the gradient of the potential function, including the pressure (or tension) and gravity-fields. Combining this with the equation of continuity leads to the relation, for one-dimensional flow,

$$\partial\rho/\partial t = kf\rho\ [(\partial\phi/\partial z)(\partial \log_e\rho/\partial z)(1 + \partial \log_e f/\partial \log_e \rho) + \partial^2\phi/\partial z^2]$$

There is good reason to believe that there does exist a function f that would suffice to validate this equation to a high degree of accuracy. Unfortunately, there seems to exist no unique relationship between the stress potential and the moisture-content of the soil, and for that reason great care must be exercised in attempts to apply the equation. Were it possible to express the stress-potential in terms of the moisture-content ρ, this would reduce to a second order partial differential equation with ρ representing the single dependent variable.

It is possible, however, without attempting to solve the equation to note certain qualitative features. For the case of water moving vertically downward into a uniform dry soil, the first term in the brackets would necessarily be positive if f increases with ρ, whereas the second term may change sign, but the left-hand member could not be negative.

Of particular interest in this connection is an article entitled "Downward entry of water into soils" by BODMAN and COLMAN, in the Proceedings of the Soil Science Society of America, 1944. For some reason that is not immediately apparent, the moisture-gradient is very great at the saturated surface in the illustrations presented. It is apparent that for these data the term $\partial^2\phi/\partial z^2$, does change sign and that the first derivative, $\partial\phi/\partial z$, is very large at the water-front.

A second article by the same authors, now in press, is likewise of special interest. As is to be expected they find a very appreciable discontinuity in the moisture-content at the boundary between soils that differ greatly in their physical characteristics. Their computations seem to reveal also an appreciable discontinuity in the stress-potential across the boundary. It is difficult to understand why there should exist such a discontinuity in the potential function. It may perhaps be noted, however, that the computations are dependent upon calibration curves that imply that there is a unique relationship between the stress-potential and the moisture-content.

It is apparent, a priori, that the moisture-content of the soil at the beginning of their experiments would determine the boundary-condition at the water-front and that this boundary-condition must have a very considerable influence on the subsequent moisture and potential distribution.

It would seem at any rate that the major task ahead involves the necessity for the development of equipment for making measurements of potential and of permeability in field soils. It is of tremendously vital importance also that a suitable function f should be obtained in order that appropriate dynamical procedures may be followed.

The problem of infiltration is one of vital practical importance. We do not know to what depth water may penetrate into the crust of the earth, but we know that the hardpans near the surface and the rock at greater depths constitute sufficiently effective barriers such that a large part of the rainfall finds its way through lateral movement into underground supplies, valuable springs, or into swamps and water-logged areas, or finally into streams and into the atmosphere by evaporation to begin the water-cycle anew.

It is vital that we should acquire broad knowledge concerning rainfall, topography, edaphology, and many of the commonplace phenomena that occur at the surface of the earth. In particular, should we not investigate the movement of the water underground? To measure and map the permeability of the soil and the hydrostatic pressure of the water beneath the surface as it varies from time to time would represent a great task, but to study these factors in significant local areas would be a profitable task to which hydrologists must sooner or later direct attention.

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DISCUSSION

ALFRED B. C. ANDERSON (P. O. Box 1663, Santa Fe, New Mexico, October 27, 1945)--Let us see if we can develop an "invariant relationship" into which soil-parameters can be substituted in order to evaluate the rate of infiltration under a particular set of conditions. Repeated applications of DARCY'S equation have been made to the flow of moisture in soil, usually with some difficulty. Both the k and the f functions are hard to define. The introduction of POISSEUILLE'S law for the flow of fluids through capillary tubes would seem to give a better understanding of the forces involved during infiltration in the soil. The derivation of this law can be found in LOEB'S book entitled the "Kinetic theory of gases" or almost any advanced classical mathematical physics text. This is

$$V = (\pi r^4/8\eta)(p_1-p_2)/\ell \qquad \text{.................. (1)}$$

where V denotes the volume of fluid that flows per unit of time out of the capillary tube of radius r and length ℓ. η is the viscosity of the fluid and (p_1-p_2) the pressure-difference, in the fluid, between the two ends of the tube. POISSEUILLE'S law somewhat resembles DARCY'S. The ratio $(p_1-p_2)/\ell$ corresponds to $\nabla\phi$ and V to v. It is more adaptable, however, and seems to be more specific to the treatment of the flow of water through small capillaries.

Consider the specific case of a vertical capillary tube, situated in the Earth's gravitational field, down which water is moving. (p_1-p_2) is then the sum of three factors: (1) The first factor is the surface tensional pull, caused by the concave air-water interface, at the bottom of the water-column, which pulls the column downward [see 1 of "References" at the end of this discussion]. This force is in addition to that of the gravitational field. If the capillary tube were placed horizontally it would pull the moisture-column horizontally. This factor would seem to be the major factor causing the lateral movement of moisture in the soil. (In the present considerations, we assume that there is an unlimited amount of water available to feed the entrance end of the capillary tube.) (2) The second factor is the weight of the column of water of length ℓ. If the water is continually supplied at the top of the capillary tube as fast as the column moves downward, ℓ and consequently the weight of the column are increasing at the same rate as the lower concave end of the water-column is moving downward. If the capillary-tube is horizontal, that is, if we consider lateral moisture-movement in the soil, this factor is absent. (3) If the top of the capillary is attached to a reservoir in which the water is at a height h above the top edge of the capillary, the resulting hydrostatic pressure on the water at the top of the capillary must also be included.

From geometrical considerations it is evident that

$$V = d(\ell \pi r^2)/dt = \pi r^2 d\ell/dt$$

so that equation (1) becomes

$$p_1 - p_2 = 8\ell\eta/r^2 . d\ell/dt$$

or

$$d\ell/dt = (r^2/8\eta)(p_1-p_2)/\ell \quad \ldots\ldots (2)$$

Since the viscosity η of liquids decreases with rise in temperature (in contrast to gases) the rate of flow of the water ($d\ell/dt$) through the capillary (or soil) should increase with rise of temperature. The rate of flow should also increase very rapidly with increase in size of the capillaries since r is squared in equation (2).

Let us transform POISSEUILLE'S law as applied to the free downward movement of water in a capillary into the form of a differential equation.

Factor (1) of (p_1-p_2) becomes [1], $2\sigma/r$, where σ denotes the surface-tension of water and r is the radius of the capillary. This factor decreases with rise of temperature [1].

Factor (2) becomes $\rho g \ell$, where ρ is here the density of water and g is the gravitational constant.

Factor (3) if present becomes $\rho g h$, where h denotes the height of the water-level above the top of the capillary tube. In practice, it is the depth of the water standing on the soil.

Substituting the sum of the foregoing three factors for (p_1-p_2) in equation (2), we have for the velocity ($d\ell/dt$) of downward movement of the water-front in the capillary

$$d\ell/dt = r^2/8\eta(2\sigma/r + \rho g\ell + \rho g h)/\ell$$

$$= 1/\ell(r^2/8\eta)2\sigma/r + 1/\ell(r^2 \rho g h/8\eta) + r^2\rho g/8\eta \quad \ldots\ldots (3)$$

or

$$d\ell/dt = 1/\ell . k_1 + k_2 \quad \ldots\ldots (4)$$

where for convenience we have set

$$k_1 = r^2/8\eta(2\sigma/r + \rho g h) \text{ and } k_2 = r^2 \rho g/8\eta$$

k_1 and k_2 are constants for a given capillary tube or soil. Radius, r, may be considered as the parameter which determines how coarse or fine the soil is. The other quantities are readily obtained from a set of physical tables.

It is thus evident from equation (4) that the velocity of downward movement or infiltration ($d\ell/dt$) is initially exceedingly great because $1/\ell$ will be great. This initially rapid rate of downward infiltration is caused by factors 1 and 3 having a very short capillary moisture-column to pull along. Eventually, after the infiltration has progressed, the water-front has moved downward and ℓ has become great, the first term on the right of equation (4) becomes asymptotically negligible. The small but constant second term k_2 then becomes significant. This term arises because of factor (2). It represents mathematically "the asymptotic value which might well be regarded as a soil-characteristic" mentioned by GARDNER. That it really does represent the infiltration characteristic of the soil is seen because it involves the radius of the capillary r. Since it involves it to the square it must depend very greatly on soil-texture.

It would seem hardly justifiable to regard this last term alone as the soil-characteristic and to forget the other two involved in k_1. They seem every bit as significant as the other term. They represent and describe the initial transient state of the infiltration process of the water into the soil when factors (1) and (3) are the preponderant factors causing moisture-movement. One might as well consider only the steady state in the treatment of electrical circuits, and disregard the electrical transients initially set up when the power is turned on, as to disregard it in the infiltration of water into the soil. The disregard of the transient state in electrical operations would cause the wrecking of many an electrical device. Disregarding it in the case of infiltration will at least give a very incomplete picture. It is true that it is much harder to study the transient state and therefore it might seem convenient to neglect it. The k_1 term should describe the initial trend of the infiltration-process, the k_2 term the later steady state.

Equations (3) and (4) would seem to be more useful than DARCY'S law in describing the infiltration-characteristics of a soil. They involve directly parameters which depend upon the soil and moisture, and the viscosity η and the surface-tension σ which both vary with temperature. They involve directly the size of the capillaries r and the density of the liquid ρ. The mechanism, or factors which cause the movement of the moisture, are also involved.

It is not hard by now to imagine that the reader is ready to rise up and condemn the foregoing application of the theory of the flow of liquids through capillaries of uniform bore (as given by POISSEUILLE'S law) to soils which are obviously composed of small particles packed closely together. The soil-capillaries are consequently anything but uniform in radius. This does not seem, however, to impair the usefulness of equation (4) or any of its modifications. When we apply equation (4) in the study of infiltration of water into the soil, what we mean by r and r^2 (if we wish to be precise) is the mean-radius and the mean of the squares of the radii along the capillary axis. For a sandy soil these averages would presumably be greater than for a clayey one. In any well performed infiltration-experiment all the quantities in equation (4), except the radius r, are readily determined either experimentally such as $(d\ell/dt)$ or from a set of physical tables. If, for a given soil, these are substituted in equation (3) or (4), then r can be readily determined by solving the resulting simple quadratic equation.

What then does this r represent practically? One might equally well ask, what does the radius or diameter we determine in the mechanical analysis of soils mean? The various methods of analyzing a soil according to its particle sizes depends upon STOKES law for the settling of perfect spheres--a law that is every bit as ideal as POISSEUILLE'S law when applied to soils. It is well known that the soil-particles are anything but spherical, being generally in the form of plates, cubes, rectangular parallelopipeds, rods, or almost any fantastic shape. Still in the final mechanical analysis-report of the soil we find the separates arranged and labeled according to particle-sizes as if they were spherical! Obviously, what is meant in the report is not that we blind ourselves and say that the particles we have separated have the radii or diameters given in the report, but rather that they have behaved as if they did have those diameters. It is a convenient experimental expedient or artifice (because of the variability of soil-particle shape) which everyone realizes is inaccurate microscopically yet macroscopically is accurate enough to serve as an admirable way of classifying soils as to texture.

This should give the clue to what we mean by r in equation (4). It is a convenient "soil-characteristic" which macroscopically can serve as a measure of the infiltration-capacity of the soil. The smaller it is, the less water will move into the soil per unit-time. It seems that whereas in the mechanical analysis of soils the particle-size is variable, in the infiltration process both this and the packing of the particles are variable. The so-called discrepancy between the r as used in STOKES law and that used in mechanical analysis is much the same as the discrepancy between the r as used in POISSEUILLE'S law and that used for the infiltration of water into the soil.

Our considerations thus far have implied that the infiltration has been going on so as to saturate the soil. Would equation (4) have any meaning in the movement of moisture in an unsaturated soil? The second term on the right of equation (3) drops out if there is no hydrostatic pressure (h=0) causing movement of moisture. If we are considering downward vertical movement in the gravitational field the third term remains; if horizontal or lateral movement of moisture, this term drops out, since then g or the component field-force pulling the water in the horizontal direction becomes zero. In any case the first term remains, as this represents the pull on the water caused by the concave air-water interface at the capillary water-front.

All of the terms remaining in equations (3) and (4) except r are readily determined in the flow of moisture in a soil in the unsaturated state. What do we mean by the r resulting from the solution of the simple quadratic equation after the experimental value $(d\ell/dt)$ and the physical constants have been substituted? It would seem that the conditions now are not different in kind from the saturated case. They are merely different in degree, down to the moisture-content at which the cavities open up and are freely interconnected by air and water-vapor. Before, the capillary moisture-column touched the capillary side-walls around their whole periphery; now, only partly. The r we now obtain by solving the quadratic equation (4) would be a measure of the infiltration-capacity of the soil at the given soil-moisture content. A clayey soil at the same moisture-content as a sandy soil would have more capillary filaments, hence a smaller r according to equation (4) because $(d\ell/dt)$ would be smaller experimentally.

At the low moisture-contents where r becomes very small we see that the last term of equation (3) and (4) also becomes negligible, since r is squared. Since r is to the first power in the first term, this one remains appreciable, however. The reverse tends to be true at high moisture-contents.

Other factors (overshadowing any of the foregoing we have considered) would seem to come into play when the moisture-content is so low that the capillary chambers in the soil become freely interconnected by air-channels. Moisture can now move in the vapor-state from places where the vapor-pressure is higher (either owing to a higher temperature or owing to the fact that the water-air interfaces are less concave than elsewhere). The problem would now resolve itself into one based upon the kinetic theory of gases. POISSEUILLE'S law would still apply, but now the viscosity η would be that of water-vapor in air. However, this case is of little importance agriculturally.

The literature relating to soils seems to have become an exceedingly fertile field for the development of a wealth of different terms for representing the same thing, especially the energy of soil-moisture. Now I meet a term "stress-potential," new to me, because during the past three years (even at present) I have had no occasion, owing to the war, to deal with subjects or literature even remotely connected with soils. Owing to the kindness of WILLARD GARDNER, I was informed by letter sometime ago that a discussion of the other various terms is contained in the Transactions of the American Geophysical Union, Part 5, pages 700-712, 1944. This I have had no chance to see yet, but presume most of the arguments there would apply here.

The term "stress-potential" has a few arguments to support it. It is certainly far from falling into the class with pF (as used in the soils-literature). The "pF of the flex point" also has no meaning as it can fall anywhere depending on the number of logarithmic cycles that are contained in the graph paper used. pF as used in the soils-literature was coined in England where strangely this identical symbol had been used for many, many years before (and still is used) to represent the smallest unit of electrical capacitance which we in this country call the "micromicrofarad" but which they (when they use the foregoing symbol) call the "puff."

The chief objection to these terms, involving potential, for representing the energy of soil-moisture, is that they seem to restrict the broad development and study of such complex moisture-systems as the system of soil-moisture, plant-moisture, and atmosphere. Such a system will operate as a single thermodynamic unit. Treating moisture-problems involving temperature, dissolved material, and a number of phases in equilibrium has often seemed to me to require a considerable amount of artificial thermodynamic trickery when using the customary concept of potential. This does not seem to occur as frequently when using the concept of free energy.

Presumably also if a student of soils goes into more advanced work he will have taken physical chemistry. If so, he probably will deal with the concept of free energy when considering different phases contained together in a system. He probably will never deal with potential (as customarily used in soils). All this may seem plausible after considering some of the standard texts used in physical chemistry such as LEWIS and RANDALL'S "Thermodynamics." Potential seems better adapted to simpler physical systems as found in electricity, magnetism, and mechanics, where temperature, different phases, and pressures are not involved. In fact the concept of potential is a very special case of the more general concept we call free energy [1, 2]. It seems hardly fair to the student of soils to compel him to throw away the seemingly far more flexible and adaptable concept of free energy for the seemingly more awkward concept of potential. Many mathematical and thermodynamic relations have been developed in connection with the concept of free energy which can with some modification be carried over to the treatment of moisture-movement [1, 2].

It does seem that the principle task ahead is to develop equipment for the measurement of the potential (free energy) of soil-moisture. It should be as sturdy and foolproof as possible. According to the literature at present, it seems that the most promising methods are based upon the measurement of either the electrical capacitance or the electrical resistance of porous blocks [3, 4, 5, 6, 7].

It has been intimated elsewhere [8] that either the electrical resistance or capacitance of porous blocks is admirably suited to the measurement of the free energy of soil-moisture. The resistance and capacitance of the porous blocks are dependent directly on the moisture-content of the block and only indirectly on the moisture-content of the soil. The porous structure of a block is fixed, and in the state of moisture-content equilibrium (between the moisture in the block and that in the soil surrounding the block) the tightness (free energy) with the water in the block is held is the same as the tightness (free energy) with which it is held in the soil surrounding the block. For example, suppose that the block is in moisture-content equilibrium with the surrounding soil. The block then has a definite moisture-content which accordingly determines the resistance, capacitance, and the tightness (free energy) with which the moisture in the block is held. The electrical resistance, the capacitance, and the moisture-content of the block will remain the same, no matter by what other soils the block is surrounded, as long as the tightness (free energy) with which the water is held in these soils is the same as that in the first soil. However, the moisture-content of the different soils may vary widely. For clay soils, the moisture-content will be high; for sandy soils, low. We accordingly see why the electrical resistance as well as the capacitance of the blocks, in all soils studied, is approximately the same at the permanent wilting percentage. They are also the same at the moisture-equivalent.

The problem then resolves itself into the calibration of the porous blocks to establish the relation between the electrical capacitance (or electrical resistance) and the free energy of the moisture in the block. This might be done by preparing a series of solutions of sulphuric acid covering a wide range of vapor-pressures of water (free energies). Each of these solutions would be placed in the bottom of a desiccator-jar. On a shelf farther up in the jars would be placed the several blocks to be calibrated with the leads from the blocks extending through the jar to the outside. The desiccators would be placed in a constant temperature-chamber and allowed to stand. In time the electrical resistance and the electrical capacitance of the blocks would asymptotically approach a fixed value depending upon the free energy of the water in the solution of sulphuric acid. At this point the free energy of the moisture in the block equals the known free energy of the water or moisture in the sulphuric acid-solution. The theoretical treatment of this has been taken up elsewhere [1].

The question still remains as to which of the various types of porous blocks are most suitable for the determination of the free energy of the moisture in a soil at different moisture-contents. Two of the desirable characteristics wanted are, that the readings be highly reproducible and that as wide a range of free energy or soil-moisture content can be covered as possible. An extended series of careful investigations [3, 4, 5, 6, 7] has shown that all the blocks give surprisingly reproducible results. Comparing the shapes of the curves obtained in the different cases we find that the electrical resistance of the four-electrode blocks of plaster of Paris seem to be variable over a much greater range of moisture-content than in any of the other cases. Significant variation extends from moisture-contents below the permanent wilting percentage to considerably above the field-capacity. In the other cases the variation becomes asymptotically constant in the vicinity of the moisture-equivalent.

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G. B. BODMAN (University of California, Berkeley, California, October 27, 1945)--The great importance of the infiltration of water into the soils of arable lands, range-lands, and watersheds in general is well known. GARDNER, in considering this subject, has combined the points of view of those who are continually confronted with the problems of infiltration in the field and of one who undertakes the development of a fundamental physical explanation of the observed phenomena, in order that a sound basis may be used for prediction of soil-behavior in regard to infiltration.

The writer is in complete agreement with GARDNER'S conclusion that field-measurements relating moisture-content to potential and permeability in soils are essential to the advance of knowledge of infiltration and other phenomena of moisture-movement. These should be made under a variety of conditions (for example, structural) for a given soil. It is believed, moreover, that in certain instances soil-columns which have been constructed in the laboratory, as well as undisturbed soil-profiles, may be used to advantage in these measurements. As an illustration of the former may be mentioned built-up columns of soil-material taken from young soils developing upon alluvium; such soils are common and extensive in parts of the West and Southwest and may be of much local importance. Methods of land-preparation and cultivation of these soils under irrigation commonly cause a large annual disturbance in an ill-developed profile, yet there appears to be a strong tendency, particularly among the coarser-textured members and those of intermediate texture, for these soils to regain several of their initial structural peculiarities soon after disturbance has ceased.

Owing to the complexity of the soil and the external influences bearing upon it, it is not to be expected that a general expression representing rates of infiltration for all soil-conditions will be immediately available. It will be desirable, meanwhile, for many experimental measurements to be made in the field for the different field-conditions concerned. Similar situations exist for many agricultural phenomena involving the soil. GARDNER has referred to the difficulties brought about by soil-heterogeneity. These are certainly of outstanding significance in infiltration-investigations and emphasize the importance of replication. Other important considerations affecting measurements where irrigation is concerned are the composition of the irrigation-water and the complications introduced by the different methods of irrigation. The influences of growing vegetation also add to the difficulties of actual measurement.

In referring to articles [see 1 and 2 of "References" at the end of this discussion] dealing with infiltration into uniform and stratified columns of soil, attention has been drawn by GARDNER to the apparent discontinuity which was found in the stress-potential across the boundary between two physically different soils. He adds that the curve used in the calculation of the stress-potential implies "a unique relationship between the stress-potential and the moisture-content" of these soils. It must be added that although this criticism is valid insofar as soil-structure is concerned, the infiltration itself is a wetting process and the method used in the calibration of the soils was also one of wetting.

The boundary discontinuity in the potential-function for the stratified soils [2] may perhaps be explained by the fairly extreme physical differences and the abrupt horizontal boundary between the soils concerned. Observations are needed upon water-movement into soils for which gradual changes exist in physical composition, and these should include a series of depth-rates of change from one texture to another.

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J. E. CHRISTIANSEN (U. S. Regional Salinity Laboratory, Riverside, California, October 27, 1945)--GARDNER has pointed out many factors that influence the development of surface-horizons and therefore affect infiltration. During the past two years, the United States Regional Salinity Laboratory has participated with other agencies in a study of water-spreading for storage of water in underground basins for subsequent use for irrigation. (The other agencies are the United States Bureau of Reclamation; Division of Irrigation, United States Soil Conservation Service; California Division of Water Resources; North Kern and Arvin-Edison Water Storage Districts; and Rubidoux Laboratory, United States Bureau of Plant Industry, Soils, and Agriculturing Engineering.) In the course of this study, permeability-tests have been made on approximately 50 undisturbed soil-cores about five inches in diameter and varying in length from 16 to 36 inches [see 1 of "References" at the end of this discussion]. Several hundred permeability-tests on disturbed soil-samples have also been made. Many of these tests were conducted over a period of several months to determine the changes in permeability that occur with time when the soil is continuously submerged. A number of field test-ponds, approximately 20 feet square, were operated by the cooperating agencies.

This study has revealed certain factors influencing infiltration that have been generally overlooked. When water is applied to a soil, an appreciable tension exists at the wetting front owing to capillary action. This results in the entrapment of air-bubbles in the larger pores [2]. During the initial phase of a permeability-test, there is generally a decrease in the permeability, due primarily to a partial breakdown of the soil-aggregates, the effect of which temporarily more than offsets the increase in permeability that occurs as the entrapped air is dissolved by the water. The permeability increases and reaches a maximum at about the time the entrapped air is eliminated. The ratios of maximum permeability to the preceding minimum permeability have varied with different soils and treatments from about 1.2 to 40. After the maximum permeability is reached, there is generally a steady decrease in permeability for a long period. When the permeability or rate of infiltration is plotted as a function of time, an S-shaped curve is generally obtained--that is, the rate first decreases, then increases to a maximum and again decreases. This same shape of curve is obtained with many of the field-ponds.

The gradual decrease in permeability that occurs after the soil is completely saturated appears to be due principally to microbiological activity in the soil. This is much more pronounced in the surface-horizon than in the subsoil.

Most infiltration-problems concern only the short-time application of water to the soil, during which there is an observed decrease in rate. The asymptotic value mentioned by GARDNER is only the leveling-off to a minimum rate. Seldom are tests, either in the laboratory or in the field, continued sufficiently long to observe the subsequent increase in rate that occurs under prolonged submergence. Nevertheless, this does occur, and is important in such problems as seepage from canals, water-spreading, and in leaching operations.

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N. S. HALL (Assistant Professor of Soil Science, Michigan State College, East Lansing, Michigan, October 27, 1945)--GARDNER stated the crux of the infiltration problem when he mentioned, "It would seem at any rate that the major task ahead involves the necessity for the development of equipment for making measurements of potentials and of permeability in field-soils." There can be no argument as to the importance of these measurements which are the summation of the physical properties of the soil. Properly measured and evaluated they will undoubtedly be the most practical measurements.

The methods designed and used by CHILDS to study the potential and flow in tiled soils will serve well for conditions of steady flow. However, since this analogous method cannot be used for changing conditions its practical value is limited.

I would like to advance a procedure that, although requiring an extended time, may have possibilities in arriving at the desired properties.

At East Lansing we are fortunate in having a Hydrologic Research Project established by the United States Soil Conservation Service in 1940 under the supervision of W. U. GARSTKA. The work is now being supervised by R. G. WHITE. During the past three years I have been privileged to examine and study some of the data. Part of the installations have been discussed by GARSTKA in the Transactions of the American Geophysical Union, Part VI, pp. 838-874 and 1060, 1944. A more detailed report will be forthcoming by WHITE.

Briefly stated, the soil-moisture of a watershed is determined by use of the electrical resistance method using porous gypsum-blocks, with temperatures measured by thermocouples installed with the blocks, and by thermohms separately located and connected to a recording potentiometer. By use of these installations, supplemented by meteorological and runoff-installations it is possible to obtain an adequate picture of water-movements in soil under varying moisture and thermal gradients. The latter appear to be very important to the movement of water in the spring.

It is not necessary to use the gypsum for the blocks used to measure the moisture-content. There are other methods developed that employ the porous-block concept that should prove more satisfactory. The advantage of the porous block is that it can be calibrated for both moisture-content and potential. The disadvantage of the use of gypsum is the rapidity with which the blocks disintegrate under high-moisture conditions.

Unfortunately such a procedure generally requires a minimum of results for two seasons, and only a limited number of soils may be investigated. However, this may be offset in part, by classifying the several soils-series of a climatic regime into profile-types and then interpolating the results on a typical series to the other series in the group. The additional information that is obtained from the described procedure more than balances out the installation-costs and time involved.

Laboratory procedures, as yet have not been designed so as to eliminate the effect of the wall of the container and the change in structure that necessarily results in the procurement of a sample.

J. C. HIDE (Associate Professor of Soils, Kansas State College, Manhattan, Kansas, October 27, 1945)--The report of the Subcommittee on Physics of the Infiltration Process and the paper by GARDNER are excellent statements.

I believe that it is essential that we obtain more information on the nature of pore-variability within soil-layers and between different layers, and the influence of this variability on the movement of moisture under the influence of capillary gradients. The nature of the surface at the time an infiltration-test is made has an important bearing on the nature of capillary-space and consequently should receive the attention of the investigator at any time that an infiltration-measurement is taken.

G. W. MUSGRAVE (U. S. Soil Conservation Service, Washington, D. C., October 27, 1945)--It is appalling to realize that on a matter so important throughout the globe as the penetration of rainfall into soil--a subject referred to as early as the writings of COLUMELLA--we actually know so little of the fundamental processes that are involved. But soils are complex and this problem is complex. Perhaps it is not so much that the importance of the problem has been ignored as that the ifficulties in its analysis have been seen. The moment we begin to study a soil, we unavoidably introduce new conditions. The soil-sample in the laboratory is something different from the same soil in its natural position and condition in the field.

The author is proposing, rightfully we think, that progress can be made by developing principles of general applicability. The question in the mind of this observer is whether or not a single permeability-factor can be developed that will be useful in its application to field-soils in general. Admittedly, much progress has been made in recent years on our understanding of the movement of water in soil and the promise of further development is probably not in the least visionary.

However, we have before us a type of problem which particularly requires caution in extending and applying laboratory-findings to natural field-soils. At least insofar as the structure of the laboratory-sample differs from that of the natural soil, caution is warranted. Most soils of natural structure contain crevices, channels, and openings that transmit free water rather rapidly, though locally, to some depth. It appears from many observations in the field that in some cases at least, a very large portion of the infiltrating water is thus transmitted. Where a dye is used and the soil-profile is dissected following application, the highly irregular nature of the downward moving water becomes evident. Dry "islands" are bypassed and left with their air-water interfaces intact, at least temporarily. The channels conducting free water act as feeders laterally for capillary water, often for a considerable time. The forces of gravity and capillarity are not always acting in conjunction. One wonders whether other forces such as thermal gradients are involved, and if so, to what extent they are effective.

This writer is hopeful and wishful that work in this field may be expanded and that this Committee may be effective in furthering such expansion. At the same time, it is hoped that we may always retain in mind the fact that the permeable medium with which we are dealing is dynamic in its properties as well as exceedingly complex.

Considerable advantage might result should it be found feasible to carry forward investigations in the laboratory and in the field simultaneously.

T. C. PEELE (U. S. Soil Conservation Service, Clemson, South Carolina, October 27, 1945--I was very much interested in the paper by **GARDNER** on infiltration and I agree with him that it would be highly desirable to develop a moisture-function that would permit calculation of permeability factors for soils at moisture-contents less than saturation.

The infiltration of water into soil might well be divided into two distinct phases. The first phase involves the entrance of water into the soil and is influenced by plant-cover, tillage-practices, rainfall-characteristics, and soil-properties which affect the degree of puddling of the surface-soil during storms or overhead irrigation. This phase determines the amounts of runoff from most of the soils in the southeastern states.

The second phase involves the movement of water after it enters the soil and might be classed as internal permeability. Since different physical factors are involved in these two phases of permeability they might well be investigated as separate but related problems. From a practical viewpoint the first phase is usually the critical factor in surface-runoff and the second phase in drainage-problems.

The paper by **BODMAN** and **COLMAN** cited by **GARDNER** emphasizes the decrease in moisture potential-gradient near the surface of the soil with increasing depth of wetting as an important cause of decreasing rates of infiltration with time. Although this may be an important factor under certain conditions, our experiments indicate that it is of much less importance in determining rates of infiltration in cultivated areas under natural storms than the decreased permeability of the surface-soil resulting from the puddling and compacting action of rainfall.

L. A. RICHARDS (U. S. Regional Salinity Laboratory, Riverside, California, October 27, 1945) The rate and amount of intake of water by soil is of use and importance in hydrologic work and measurements of these quantities have been made for many soils. It would be useful in correlating accumulated data and applying our experience to new situations if the fundamental processes underlying infiltration were fully understood and could be embodied in a general dynamical equation.

Field-measurements with tensiometers [see 1 of "References" at the end of this discussion] have indicated that during infiltration the moisture a short distance beneath the surface is under tension and therefore generally the flow of water in unsaturated soil is a complicating feature of the infiltration-process. **GARDNER** has indicated some of the difficulties involved in a dynamic formulation of the problem. **BODMAN** and **COLMAN** in the paper cited by **GARDNER** have made a valuable contribution to measuring techniques and have amply demonstrated some of the advantages of inquiring into relations among such factors related to infiltration as potential, potential-gradient, permeability, flow-density, and moisture-content.

Unfortunately the usage with respect to nomenclature and units for soil-moisture work is very much in a formative state, and extra care is required in reading the literature to ascertain the intended meaning for various quantities. Moisture-potential and stress-potential as used by the above authors may be cited as an example. The former is used in a restricted and, hence, different sense from that originally proposed, and the latter has been introduced without definition. At some appropriate future time a discussion of the nomenclature in this field might be profitable.

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WILLARD GARDNER--I have read with care the comments concerning the article on infiltration. It is my impression that when we come fully to understand each other we shall find very little disagreement regarding vital points. Although some things I may say may be somewhat controversial, it seems to me the comments have all been very fine nevertheless.

I believe I am in complete accord with **MUSGRAVE** in the hope that we may succeed in defining infiltration-capacity in such a way that it may be reliably measured in localities where such measurements may be desirable. This characteristic of profile will of course vary from time to time about a mean, but even then if we can associate numbers representing infiltration-capacity with our soil-maps they would, it seems to me, have great value.

Permeability is of course a distributed scalar point characteristic, that is, it will in general vary from point to point in the soil-profile. In some cases where it varies in a simple definable way that could be determined experimentally, we might be able to compute the infiltration-capacity in terms of this variable permeability and of the boundary-conditions imposed. By boundary-conditions I mean such things as the position of the water-table. Such irregularities as open cracks, open holes left by burrowing animals, or sand-and gravel-pockets, would make it extremely difficult and perhaps impossible for us to make such a computation with precision, but they would not necessarily interfere with the measuring of this profile-characteristic. The influence of these heterogeneities would of course be reflected, as they should, in these measurements.

We may discover that we do not need to know much about the dynamics and the thermodynamics of soil-moisture in order to obtain these mean values of the infiltration-capacity for various localities. On the other hand, this knowledge will be of inestimable value in helping us to understand and explain the devious problems that must confront us in any large scale effort to find out where the water from rain, melting snow, and irrigation goes, and at the same time help us to exercise some degree of control over the water that moves constantly everywhere under the surface of the soil.

I agree with ANDERSON that we shall find thermodynamics indispensable in studies of soil-moisture, but I am not sure I can concur with him in all his suggestions regarding free energy. His statements are, of course, constructive and possibly all correct. I have in mind at the moment his apparent dislike for the term potential.

EPSTEIN, on pages 20 and 21 of his textbook on Thermodynamics points out an intimate relation between the concept of an exact differential and a potential function. On page 89 he defines what he calls the thermodynamic potential by means of a thermodynamic equation involving its differential. ANDERSON and others seem to prefer the name free energy. One of the terms in this definition is the much discussed term, vdp, which I write with the lower case v in order to refer it to unit mass. The term of which this is the differential has been given such names as capillary potential, moisture-potential, pressure-potential, and free energy, and I proposed recently the name stress-potential. Normal (as distinguished from shearing) stress may be a pressure or a tension and it seemed to me that to use the term stress-potential to represent this important function would assist in avoiding the necessity of distinguishing explicitly between positive and negative pressure. This term would in itself not be an exact differential unless v is either constant or a function of p.

It is perhaps not necessary that we should discuss at length the suggestion of ANDERSON regarding the restricted application and significance of the stress-potential. I think it should be emphasized, however, that although the law of conservation of energy is stressed in thermodynamics, NEWTON'S second law of motion seems to be almost entirely suppressed. It seems to me that no one would seriously question the fact that there is a tremendously wide and important field of mechanics in which thermodynamics is almost completely suppressed. Although the temperature is implicitly involved in the coefficient of permeability, the DARCY law purports to be nothing more nor less than an application of NEWTON'S second law--at least for the special case in which the acceleration vanishes.

The question of greater concern, however, would be the question as to the physical character of the thermodynamic potential and of the various terms of which it may be composed when it enters into a physical problem. The terms Ts and pv of course have the dimensions of energy per unit mass, as do the others, but it is immediately apparent that the integral $\int vdp$ may be made to increase without bounds so long as v may be regarded as constant without any source of energy whatever. I believe it is erroneous to use the expression "energy of soil-moisture" as a synonym for thermodynamic potential. For example, whereas the thermodynamic potential per unit mass is the same in a liquid as it is in the vapor with which it is in equilibrium at any given temperature, it requires approximately 539 calories to evaporate a gram of water at 100°C, and only a small fraction is used in the work of expansion. Is it not possible that the expression "free energy" is in reality the misleading name for the thermodynamic function designated by EPSTEIN and others as the thermodynamic potential?

Attention should be called to the fact that there seems to be no apparent reason why the classical equations of the dynamics of viscous fluids should not apply in the liquid domain of a moist soil even though it is not saturated. However, inasmuch as the bounding interfaces are so terrifically distorted, one of them being also a free surface, it is quite impossible to apply these equations without resorting to some sort or other of macroscopic point of view. The direction of the forces of adhesion would vary in such random fashion that they would not contribute a macroscopic force in any direction.

Inasmuch as the density in the DARCY equation is constant, the stress-potential ψ defined by the differential expression,

$$d\psi = (1/\rho)\,dp \qquad (1)$$

is an exact differential. The fundamental assumption of the DARCY law is therefore that the friction-force resisting movement of the soil-moisture is directly proportional to the macroscopic velocity. With this assumption it is necessary only to write down NEWTON'S second law (for statics) in order to infer this tremendously significant equation, which, for the case of one-dimensional flow, may be written in the form,

$$v = -k[(1/\rho)dp/dz - g] \qquad (2)$$

For the benefit of those who are familiar with the vector notation, this equation may be written in the general form,

$$v = -k\nabla\Phi \qquad (3)$$

in which Φ is the potential function consisting of the two terms,

$$\Phi = p/\rho + \Phi = \psi + \Phi \qquad (4)$$

Φ being the gravitational potential and p the hydrostatic pressure.

I repeat what was emphasized in the previous paper, that we must take account of the fact that in a great number of important practical cases the soil-moisture with which we are concerned is moisture in soils that are not saturated.

It is apparent that the permeability should increase with the moisture-content, and the introduction of the undetermined function f would purport to account for this increase provided an appropriate function may be found. The only change, therefore, in the form of the DARCY equation would be the introduction of this function as an additional factor,

$$v = -kf\nabla\Phi \qquad (5)$$

but the important question is: should the density ρ in the expression for ψ be construed as the macroscopic density, that is, the mass of moisture per macroscopic unit of soil, or the density of the soil-water itself? It is to be admitted that the procedure in either case is to include an additional empirical macroscopic step in the analytical procedure that is not implied in the original form of the DARCY law.

Without including the details, the alternative forms of the final equation to be obtained by combining the modified form of the DARCY law with the equation of continuity are presented below, the expression σ being introduced in the second equation to represent the density of the soil-water, whereas ρ is retained for the moisture-content of the soil per unit macroscopic volume.

$$\partial\rho/\partial t = k\rho f[g(\partial\log_e f/\partial z + \partial\log_e \rho/\partial z) - (1/\rho)\partial\log_e f/\partial z\;\partial\rho/\partial z - (1/\rho)\partial^2 p/\partial z^2] \qquad (6)$$

$$\partial\rho/\partial t = k\rho f[(g - (1/\sigma)\,\partial p/\partial z)(\partial\log_e f/\partial z + \partial\log_e \rho/\partial z) - (1/\sigma)\partial^2 p/\partial z^2] \qquad (7)$$

I present these alternatives without having considered carefully the question as to which one seems to me to be the most appropriate. I would like to repeat, however, that we do need a dynamical approach to the problem of the movement of moisture in the soil however fruitful may be the methods of thermodynamics in connection with the physics of the soil and the soil-moisture. I should like to repeat also for emphasis, that the problem of the infiltration of water into the field-soil may involve difficulties that cannot be completely resolved by the methods of mechanics or of thermodynamics. This should not, however, discourage us in our efforts to do the best we can.

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(See also pp. 94, 102, and 108)

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INTERNATIONAL SCIENTIFIC COOPERATION[1]

F. J. M. Stratton

The gradual easing of restrictions on travel and on the general release of scientific discoveries has made it practicable once more to arrange international meetings of men of science. The General Assembly of the International Council of Scientific Unions will meet in London on July 22-24, 1946 [the last General Assembly of the Council was in London in May 1937; the next General Assembly was to have been held in Copenhagen in 1940, to be preceded by a meeting of the Executive Committee in October 1939, but the outbreak of the war necessitated that both these meetings be canceled]. Meanwhile its Executive Committee has held a meeting [December 4-5, 1945] in London, attended by representatives of most of the International Unions adhering to the Council. [The following members of the Council and guests were present: Dr. H. R. Kruyt of Holland (Vice-President and President); Dr. J. A. Fleming of U. S. A.; Prof. B. Nemeč of Czechoslovakia; Sir Harold Spencer Jones of Great Britain; Prof. J. E. Proudman of Great Britain; W. D. Lambert of U. S. A.; Prof. E. de Martonne of France; Prof. M. J. Sirks of Holland; Prof. F. J. M. Stratton of Great Britain (General Secretary); Dr. Vranek and Mrs. Malterre of France (representing the International Organization for Intellectual Cooperation), and (during part of the time) Sir Henry Dale, past President of the Royal Society of Great Britain; Dr. A. V. Hill, General Secretary of the Royal Society of Great Britain; Prof. P. M. S. Blackett of Great Britain; Dr. L. H. Lampitt of Great Britain; Prof. R. M. Field of U. S. A.; and Prof. J. M. Burgers of Holland. Apologies for absence were reported for Prof. M. S. Siegbahn of Sweden, Vice-President of the Union; Sir Edward Appleton of Great Britain; Commandant Dorsimont of France; Prof. A. Cotton of France; Prof. O. Bergstrand of Sweden; and Prof. F. Verdoorn of Holland, now resident in the U. S. A.]

In welcoming the Committee at its opening session, Dr. A. V. Hill, General Secretary of the Royal Society of Great Britain, pointed out that science in its own interest must remain an international concern and that the future of civilization itself depended upon the close cooperation of scientific men throughout the world. The complete address of welcome is as follows:

"Throughout the 283 years of its existence the Royal Society has been intimately concerned with promoting cordial and familiar relations between British scientists and those of other countries. For 222 years, indeed, it has had a special officer, the Foreign Secretary, whose duty it is to deal with communications with foreign scientists. The Royal Society, after the first world war, took a leading part in the formation of the International Scientific Unions and the International Council of the Scientific Unions; and during the second world war it maintained and enlarged both its connections with foreign scientists so far as they were within reach and its faith that these international organizations must be started up again as soon as possible after the war was over. It is a particular pleasure, therefore, to the Society that the International Council is meeting here today in its rooms [Burlington House]; and it is my most agreeable duty to give you all the warmest possible welcome from the Society--and indeed from all British scientists.

"The course of world events has made it even clearer than it ever was before, not only that science in its own interest must remain an international concern but that the very future of civilization itself depends upon the close cooperation of scientific men throughout the world. We are, after all, the best example of international cooperation. I would go further still. For well over 2000 years medicine has been taught not only as a matter of observation and science but as a field for the application of high ethical principles. Without some system of ethics governing the behavior of its practitioners medicine would be well-nigh impossible; and without medicine civilization as we know it would be impossible too. We have now reached the time when a common standard of ethical behavior is just as important in science as in medicine. This does not mean that scientists as such are called upon to spend their time and effort on social, economic, and political affairs any more than medical ethics demands that sacrifice of their special skill and knowledge by medical people. It does, however, mean that in standards of truthfulness and integrity, in readiness to cooperate with other scientists of good will everywhere, and in refusal to use the common knowledge, prestige and power of science for base, harmful and selfish ends, scientists should feel bound by an honorable and unbreakable obligation--as a duty to themselves, as a duty to their fellow scientists, as a duty to their fellow men.

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[1] Dr. Stratton, who was General Secretary of the International Council of Scientific Unions, has prepared this article which summarizes, with some background as regards the Council's history, the meeting of the Executive Committee of the ICSU which was held in the rooms of the Royal Society of Great Britain on December 4-5, 1945. There have been added in Dr. Stratton's article, as indicated by enclosures in brackets, certain particulars from the minutes of that meeting which are of general interest to geophysicists in connection with Dr. Stratton's paper-- J. A. Fleming.

"The International Council meets today in a time of special difficulty, and of very special opportunity. What it decides itself to do, or to recommend to the International Scientific Unions, will be done or recommended by scientific men representing the common interests and heritage of science, not the views of political or national organizations; and it may have a very important bearing on future relations. No doubt much of your time will be spent on details of organization and machinery. That is necessary, for it is common knowledge that the International Council in the past was not as effective as an agent, indeed some of the Unions were not as effective agents as they might have been; and plans to make them more effective must be properly worked out. But I hope that a little time at any rate may be found to consider the larger and more general problem of scientific ethics. No doubt it will be impossible to reach any final conclusion in two days--the growth of medical ethics took hundreds of years--but there is equally no doubt that ultimately the ethical question is among the most important which international science has to answer. We scientists know very well that a problem is usually more than half solved when it has been clearly stated in unambiguous terms; and before it disperses from the meetings of these two days the International Council may at least have been able to make a start towards the unambiguous statement of the ethical problem which faces scientific men--and indeed faces the world--today.

"I will not keep you longer; you have much practical work to do. But before I end may I say once more to the International Council, particularly to those of its members who come from overseas, that the Royal Society offers its warm welcome--and I am proud to have the duty and privilege of offering it."

The heavy toll of recent years on those prominent in the field of international science was revealed by the list of members of the Committee who had died since its last meeting: Members--Il Marchese Marconi and Baron Joji Sakurai; Vice-Presidents--Sir Arthur Eddington, President of the International Astronomical Union; Prof. Nicola Parravano, President of the International Union of Chemistry; Sir Albert Seward, President of the International Union of Biology; General Secretaries and others--Prof. H. Abraham and Dr. M. Philippson, General Secretaries of the International Union of Pure and Applied Physics; and General J. E. R. Bourgeois, former Vice-President, representing the International Union of Geography; Sir Henry Lyons, General Secretary of the International Council of Scientific Unions.

The President of the Council, Prof. C. Fabry, had been compelled to resign on account of ill health (he has died since) and Dr. H. R. Kruyt of Holland was elected President, Dr. Elmer D. Merrill of the U. S. A. being elected Vice-President in his place.

The International Council, or rather its predecessor the International Research Council, was created after the first world war and took as its main task the creation of the various International Scientific Unions. In the early days the Council exercised a certain amount of control over these Unions in such questions as membership and finances. As the individual Unions became established and strong this control proved irksome and a change took place in the relative positions of the Council and the Unions, largely the work of the then General Secretary of the Council, the late Sir Henry Lyons. Now it would be fairer to say that the Unions control the Council, the majority of the members of the Executive Committee being the representatives of the Unions. The officers and two members of the Executive Committee only are appointed by the General Assembly at which the national adhering organizations have a preponderating vote.

The International Unions meet in General Assembly as a rule once in three years for discussions on the fields of knowledge lying within their purview; by means of numerous committees of specialists work is carried on between the meetings and is reported on and discussed at the meetings of the General Assembly. Ninety-two such committees have been reported as working in the various International Unions, their activities covering a very wide field of knowledge. Each Union also appoints at its General Assembly a small Bureau of officers who are able to answer for the Union as a whole between meetings. Some of these have been badly broken up during the war years and are only now being rebuilt.

In addition to the International Unions there are in existence a number of International Congresses which meet from time to time in different countries but have no continuity of active existence between meetings. Broadly speaking, it would be safe to say that those who have been actively concerned with these Congresses and have pleasant recollections of their scientific discussions and fellowship do not desire to change them into international unions. The weakness of their position, however, is the lack of a body between meetings that can answer for the subject covered by the congress and that can nominate the most suitable members for cooperation with unions desiring their help. Borderline subjects needing international study are catered for by joint commissions between the various Unions. It would be a help if an international congress would appoint a bureau to function between meetings to which the various requests for assistance or advice could be addressed. This is done in some cases already. In other cases Unions and Congresses both exist. The General Assembly of the Union meets at the same place as the Congress and within a day or two of the Congress meeting. Elasticity of organization is desirable to meet the different needs and outlook of workers in different fields.

Joint commissions of the Unions have been active for over 20 years in some cases, for instance, the Joint Commissions on Latitude Variation, On the Determination of Longitudes by Wireless, and on the Bureau de l'heure, in which both the Unions of Astronomy and of Geodesy and Geophysics are concerned. Some joint commissions are only planned as yet, for example, a commission on Ionospheric Research which it is hoped to set up in due course with members from the Unions of Astronomy, Geodesy and Geophysics, Radio-Science and Physics. Other joint commissions proposed at the recent Executive Committee meeting of the Council are on Oceanography (Biology and Geodesy and Geophysics), Physico-Chemical Constants (Physics and Chemistry), Viscosity (Chemistry, Biology, Geodesy and Geophysics). In the work of this last committee it is hoped that means will be found to secure the cooperation of the International Congress of Applied Mechanics.

In addition to joint commissions between the Unions, which the Council may help to arrange, the Council also appoints committees of its own such as the Committee on Solar and Terrestrial Relationship, in which are members from the Unions of Astronomy and Geodesy and Geophysics. Another committee of the Council is one on Science and Social Relations (CSSR) appointed in 1937 to survey the most important results obtained and the directions of progress that are opening and of points of view brought forward in the physical, chemical, and biological sciences with reference to their interconnection, the development of the scientific picture of the world, and their practical application in the life of the community. In response to the inspiring and untiring energy of Prof. J. M. Burgers, Secretary of this Committee, reports were being received from countries and Unions in the years 1938-39 in readiness for collation and publication when the outbreak of war interrupted the work. Some of these reports, such as one on the Social Aspects of Science in Estonia, are now only of historical interest and the Committee has now been asked to prepare a survey of the published views of scientific bodies on the problems now arising in connection with researches into such matters as nuclear physics and drugs. Such a survey may enable the Council to make a reasoned pronouncement, supported by the full weight of international science, on the ethical problems which face scientific men in particular today--thus accepting the challenge offered by Dr. Hill to the Executive Committee in his address of welcome at the recent meeting. A valuable contribution to the work of the CSSR will be provided by the annual reports on the work of the various Unions which the Council hopes to receive in future and to distribute widely.

The Council is linked by a convention to the International Organization for Intellectual Cooperation of the League of Nations; the convention defines the separate spheres of action of the two bodies and the various ways in which each can help the other. While the fate of the International Organization of the League of Nations is uncertain at present, there has come into existence the United Nations Educational, Scientific, and Cultural Organization (UNESCO). At the recent conference at which UNESCO was formed a resolution was adopted, on the proposal of the delegation from the United States, asking the preparatory commission to invite its Executive Committee to examine with the International Council of Scientific Unions such methods of collaboration as might be practicable to strengthen the programs of the two organizations within the limits of their joint concern; the Executive Committee of the Council has appointed a Committee to consult with representatives of UNESCO and it is hoped that much may arise from their discussion to the mutual advantages of both bodies. [The Committee appointed by the International Council of Scientific Unions for this purpose consists of President Kruyt, General Secretary Stratton, and W. D. Lambert.] The clause introducing this resolution may well be taken as defining the task now facing the International Council of Scientific Unions:

"Il est urgent de reconstituer et de développer les moyens permettant aux savants de tous les pays d'échanger des renseignements et de travailler en commun au développement de la science et à son utilisation au service de l'humanité."

Gonville and Caius College,
Cambridge, England, December 1945

[The Editors briefly summarize below certain actions taken during the meeting of the Executive Committee which are of interest to geophysicists generally.

It was agreed that countries that have paid no subscription since 1936 be invited to send delegates to the General Assembly in 1946 but that they should be informed that arrears up to and including 1939 must be paid before their delegates could attend and vote.

It was agreed to start subscriptions from 1946, but to invite the remaining adhering organizations to pay their contributions as from the last date of payment up to and including 1945 and in any case up to and including 1939.

The General Secretary reported the retirement of the Principality of Monaco and the change of adhering organization for South Africa from the Government to the National Research Council and Board (now the Council of Industrial and Scientific Research). It was agreed that a letter be sent to the Russian Academy of Science, that Bulgaria, Finland, Hungary and Roumania be invited to the meeting of the General Assembly in 1946, and that no invitation could be sent to Estonia and Latvia. It was also agreed not to invite Japan to the General Assembly in 1946 and to ask the General Assembly to leave future action with regard to Japan to the discretion of the Executive Committee.

Dr. Vranek of the Institut International de Coopération Intellectuelle explained that the position of the Organisation Internationale de Coopération Intellectuelle de la Société des Nations would be dealt with in due course by UNESCO and that the executive body, the Institut International de Coopération Intellectuelle had reopened and resumed activities with a reduced staff. They were prepared to help the ICSU and the Unions as previously.

It was agreed to maintain the existing convention for the present and to await further developments.

Various suggestions which had been received by the General Secretary from adhering organizations and which had been circulated to members of the Executive Committee were discussed. It was agreed: (1) That the best course at present was to rebuild international scientific cooperation on existing organizations. (2) That the Council should help existing unions in all ways possible. (3) That any question of subdividing Unions be left to the initiative of the Unions themselves. (4) That international scientific congresses as held, should be approached with a view to Unions being formed, special attention being paid to the needs of other Unions for joint commissions. (5) That the Committee conferring with UNESCO consider the desirability of a diplomatic convention and of the aid in this connection available from UNESCO. (6) That the same Committee discuss with UNESCO the support of substantial international services of a permanent character. (7) That the Executive Committee should meet annually and receive and publish an annual report on the activities of each Union, especially on any development calling for the cooperation with other Unions. (8) That joint Committees of the Unions be organized by the ICSU, the members to be nominated by the Unions concerned. (9) That where essential the finances of these joint Committees be the responsibility of the ICSU. (10) That adhering organizations be asked from time to time for suggestions as to subjects in which International Unions are needed.

The annual subvention for 1946, if found necessary and desirable, was authorized for the Committee on Solar and Terrestrial Relationships. A grant of £180 for the publication of the Quarterly Bulletin of Solar Activity was made for 1942-44. A grant of £50 for 1945, subject to the approval of the President of the International Astronomical Union, was made to Prof. W. Brunner.

A letter from Dr. Sirks was read on behalf of the Central Bureau for the Cultivation of Fungi, a body of international importance in the field of agriculture and industry. He proposed, and Prof. Nemeč seconded, a resolution calling for international financial support. It was agreed to refer the matter to UNESCO and it was emphasized that the scientific controls must remain with the Unions.

A letter from Prof. Verdoorn was read on the question of an annual report on all international scientific organizations and on an international professional scientific journal. It was agreed that annual reports from the Unions should be published with a wide distribution but that the ICSU should not attempt to publish a separate journal.

It was resolved to propose certain changes of Statutes to the next General Assembly to be held in London July 22-24, beginning at 11:00 July 22.

With reference to the address of welcome of Dr. Hill, and a letter from Prof. Siegbahn on the publication of nuclear physics researches, it was agreed to ask the CSSR to prepare a survey on the published scientific attitude to such questions as the use of atomic energy, the study of drugs and foods, etc., and to report to the Executive Committee before the next General Assembly.

It was agreed (a) that the General Secretary prepare an article on its activities to be offered to scientific journals round the world and to be sent to members of the Executive Committee. (b) That members of the Executive Committee should send to the General Secretary by December 15 lists of suitable journals to which copies of the article should be submitted. (c) That members of the Executive Committee should send to the General Secretary lists of suitable recipients (academies, institutions, libraries, universities, etc.) for an extended list of recipients of the publications of the Council and of the Executive Committee--J. A. Fleming.]

UNION, SECTION, AND COMMITTEE ACTIVITIES

UNION ACTIVITIES

Meeting of the Executive Committee of the Union--A meeting of the Executive Committee of the Union was held in Washington on January 25. On the agenda were plans for the Twenty-Seventh Annual Meeting, setting up of the machinery for elections by mail ballot in 1947, and reports of various committees. The General Secretary also reported briefly upon the attendance of R. M. Field, W. D. Lambert, and J. A. Fleming at the Executive Committee meetings of the International Council of Scientific Unions and the International Union of Geodesy and Geophysics at London and Oxford in December, 1945. A detailed report of the meeting of January 25 will be published in the April issue of the Transactions.

Ernst Cloos of Johns Hopkins University has been appointed a member of the Division of Geology and Geography of the National Research Council to represent the American Geophysical Union. His appointment is for a three-year term beginning July 1, 1946. He is succeeding John A. Fleming.

Cooperation with American Standards Association, Committee on Photography, Z38--G. C. Mattison, representative of the American Geophysical Union on the Committee on Photography, Z38, of the American Standards Association, advises that the next meeting of the Committee is scheduled for May 10. Members having suggestions bearing on such matters should communicate with Commander Mattison, Room 631, Federal Office Building, 90 Church Street, New York 7, New York. Please send copies of communications to the office of the Union also.

Cooperation with the National Roster--George A. Works, Director of the National Roster of Scientific and Specialized Personnel, has advised that 2,800,000 copies of the leaflet "The job of the Geophysicist" have been printed and that more will probably be printed later. This leaflet, also referred to as Occupational Brief No. 26, is being distributed largely through separation centers of the Armed Forces. Dr. Works advises that it is meeting a very definite need, both in the Armed Forces and among civilians.

The American Geophysical Union cooperated actively in its preparation, and it was in connection with this that the questionnaire that formed the basis for the paper "Education in Geophysics" [Trans. Amer. Geophys. Union, v. 26, pp. 463-476, 1945] was sent out. There are frequent calls for reprints of this paper, which are now available. Three corrections or omissions relating to the Table in that paper have been received. Because some institutions failed to respond to the questionnaire, there are a number of omissions that will be compiled as a supplement in a later issue. Word concerning such omissions will be appreciated (see Corrigendum, p. 120).

A second publication relating to Geophysics is in preparation for publication by the National Roster. On this the American Geophysical Union has likewise cooperated actively. It is somewhat longer than the Occupational Brief and is entitled, "Vocational monograph on the profession of Geophysics." Copies should be available sometime in March.

SECTION ACTIVITIES

Section of Hydrology

Regional Meetings--The South Pacific Regional Committee of the Section of Hydrology plans to hold a two-day meeting, probably in cooperation with the Western Snow Conference, on February 27 and 28. It will be held in Sacramento, California.

The North Pacific Regional Committee of the Section of Hydrology plans to hold a meeting in the Pacific Northwest sometime in June, probably in cooperation with the Northern Rocky Mountain Regional Committee and other organizations.

First Meeting of the Washington Group--About 70 local members affiliated with the Section of Hydrology attended a luncheon meeting in the South Building, United States Department of Agriculture, Washington, D. C., November 29, 1945.

After lunch, D. B. Krimgold, acting chairman, briefly reviewed events leading to the meeting and to the formation of a Washington Group. Of some 70 members replying to the several questions included in the notice of the meeting, only three did not favor meetings of a Washington Group.

The greatest number favored quarterly luncheon meetings devoted to general subjects such as descriptions of hydrologic work of various agencies.

K. H. Beij, on behalf of the Executive Committee of the Section of Hydrology, stated that the formation of a Washington Group was approved by the Executive Committee, and that a permanent committee to manage the affairs of the group should be elected by the group and approved by the President of the Section. With the tacit consent of those present, he appointed D. B. Krimgold, C. W. Thornthwaite, O. E. Meinzer, and E. N. Munns as a committee to consult with local members and submit nominations for a permanent committee.

Dr. Meinzer introduced N. H. Darton, who spoke briefly on the earliest work of the Water Resources Branch of the Geological Survey.

Mr. Krimgold introduced Franklin F. Snyder, who spoke on the forecasting of water stages of the Rhine from December,1944 to May, 1945, in which forecasting he took a prominent part. The success of the project demonstrated conclusively the valuable contributions which hydrology can make to the work of the Armed Services in time of war.

The meeting adjourned at 13^h30^m.

K. Hilding Beij, Acting Secretary

Second meeting of the Washington Group--The Washington Group of the Section of Hydrology will hold its second meeting in Barker Hall of the Y. W. C. A. at noon on Monday, February 15, 1946. Merrill Bernard of the United States Weather Bureau, recently returned from Moscow where he was attached to the American Embassy as Meteorological Attaché, will speak. Arrangements are being made by Bernard Frank of the United States Forest Service.

COMMITTEE ACTIVITIES

Standing Committee on Nominations--In accordance with the provisions of the Statutes and By-Laws adopted July 31, 1945, a Standing Committee on Nominations has been appointed, as follows: R. H. Weightman, United States Weather Bureau, Chairman; J. B. Macelwane, Institute of Geophysical Technology, St. Louis University; C. A. Heiland, geophysicist, of Denver; F. J. Viehmeyer, University of California; and W. W. Rubey, United States Geological Survey. This Committee has been charged with the responsibility of setting up the machinery for elections by mail ballot in accordance with the provisions of the revised Statutes and By-Laws, bringing the election procedures adopted by the Sections into coordination with the Union procedure, as well as the nomination of candidates for officers of the Union to be elected in 1947.

Standing Committee on Membership--H. F. Johnston, efficient Chairman of this Standing Committee since July 1944, found it necessary to resign due to protracted illness. G. W. Musgrave of the Soil Conservation Service, Chairman during the immediately preceding administration, was appointed on November 26, 1945, to fill the unexpired term to June 30, 1947. Irwin Roman was appointed to the Committee December 15, 1945,to represent the Section of Terrestrial Magnetism and Electricity.

Chairman Musgrave has entered into a program to bring many qualified persons, not now members, into the Union. He sent individually signed and addressed letters to the entire membership of 2650 members and associates to enlist their aid in calling the attention of the American Geophysical Union to many of these qualified persons. Early indications are that this appeal will receive a good response.

During the last quarter of 1945, 103 proposals for membership were received, sponsored by 142 members. Each of 109 members sponsored one new member; each of 21 sponsored two; four sponsored three; three sponsored four; two sponsored five; one sponsored seven; and two sponsored 14. It is thus clear that the membership is recognizing more and more its responsibility in providing opportunities for qualified individuals to affiliate with us.

Standing Committee on Budget--C. H. Swick has resigned as Chairman of this Standing Committee and R. M. Wilson of the United States Geological Survey was appointed on January 15, 1946, to fill his unexpired term to January 30, 1947.

Special Committee on Surveys and Maps--C. H. Swick resigned as Chairman of this Committee because of his recent retirement from his official duties with the United States Coast and Geodetic Survey. Frank S. Borden of the United States Coast and Geodetic Survey and member of the Committee, was appointed Chairman on January 10, 1946, to June 30, 1947.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

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PRECISE CONTROL SURVEYS FOR BASIN AND RAIL EXTENSION OF DAVID W. TAYLOR MODEL BASIN

Lansing G. Simmons

Abstract--The purpose of this paper is to cover the technical details of the measurements, and results derived from them, made for the control of the basin and rail extensions of the David W. Taylor Model Basin, U. S. Navy, Carderock, Maryland. There are two basins in the present building, running approximately east and west, the south or deep basin, and the north or high-speed basin. These are about 1300 feet in length. Construction is now under way for the extension of these basins, and the building to enclose them, in an easterly direction for a distance of about 1800 feet.

Need for precision--Each basin is flanked by a concrete wall supporting a heavy rail on either side. The south rail in each case guides as well as supports one side of the towing carriage; the north rail merely supports the other side of the carriage. The precision surveys are needed to provide the contractor with means of setting very accurately the forms for the four basin walls and particularly the templates which space the track bolts and posts before the concrete is poured. The tolerance given the contractor for the bolts and posts is but 1/8 inch in any direction. The rails, particularly numbers 1 and 3 which guide the carriage, must finally be aligned to a greater precision than this. It is expected some form of wire suspension method will be used for the final rail alignment after the building has been completed. All rail supporting and securing appurtenances, however, must be placed within the 1/8 inch tolerance during the construction period in order that they will fall within range, both vertically and horizontally, of the final alignment. The vertical alignment required is parallel to still water surface and was obtained, in so far as surveying processes are concerned, by ordinary geodetic leveling. The final vertical alignment of the rails will result from a special process of water leveling from the water in the basins.

Plan of survey--The basis for all elevations of the survey is the top of a small steel plug marker set by the Model Basin, near the base of rail number 3 at station 12 + 64 (see Fig. 1). The basis for all alignment work is the existing center line of rail number 3 and the starting point for all distance measurements is the center of rail number 3 directly opposite (at the same station) a cross scratched on the steel plug marker. A special device was built in the shops of the Model Basin which, when clamped to the head of the rail, permitted an accurate projection of the cross on the marker to the center of the rail. This same instrument was designed also to locate the center line of the rail very accurately, wherever this was needed (see Fig. 1, under tripod).

The Model Basin has a "station" numbering system based on a zero station at the west end of the present building. The plan of the survey was to measure east 176 feet along rail 3 from station 12 + 64 and establish a station at 14 + 40, the first even 120-foot station east of the present basin building. This point, A, and the line of rail 3 formed the basis for the rectangular survey of D-E-F-C (see Fig. 2). The north-south lines were made perpendicular and the east-west lines made parallel to the line of rail 3. The east-west lines were set about 360 feet north and south of the center line of the proposed basin building in order to clear the construction area completely. Marked monuments were spotted along these lines at every even 120-foot station out to station 34 + 80. The center lines of rails 3 and 1 were projected east about 2108 feet from point A and marked at points L and K. Points E, L, K, and F are at station 35 + 48, very nearly. The line of rail 1 is not squared with the survey as it converges slightly toward the line of rail 3 at the rate of about 0.5 mm per 100 feet. Doorways were cut through the east wall of the existing basin building to permit the projection of the rail lines.

The monuments and their purpose--Monuments A and B were set just outside the existing building at station 14 + 40, on the rail lines in order that a theodolite might be set over them in extending these lines. Monuments L and K were set about 300 feet beyond the construction area to mark and preserve the rail lines, as extended, during the construction work. The 120-foot transverse monuments on the two east-west lines, beginning at C and D (station 14 + 40) and ending at station 34 + 80, were established as distance control for the contractor in setting the forms and templates for the 40-foot sections of the new basin walls. This distance control is projected into

STEEL PLUG MARK
STATION 12+64.00
ELEVATION
FOR BASIN EXTENSION
17 AUGUST 1944

Fig. 1--Station 12 + 64, showing location of steel plug marker, device for projection of cross on marker, and 10-inch theodolite equipped with micrometer eyepiece for measuring small angles in line projection

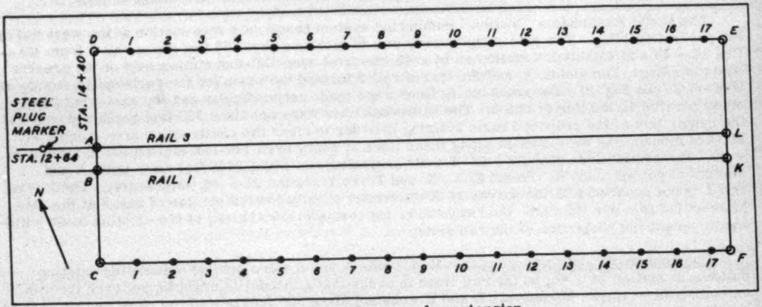
D
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
E
STA. 14+40
STEEL
PLUG
MARKER
STA. 12+64
A
RAIL 3
L
K
B
RAIL 1
N
C
F

Fig. 2--Plan of survey for extension

the construction area by "wiggling in" a transit on the line between two corresponding monuments to the north and south. Monuments E and F were set to square off the rectangle with L and K and thus provide a check between the measurements along the two east-west lines.

All monuments, with the exception of L and K, are concrete columns eight feet in length and one foot in cross section, set five feet in the ground, and project three feet above the ground (see Fig. 3). The lower portion was cast in the ground. The top eight inches of concrete was not poured until a rather accurate preliminary survey was completed to locate the final positions of the bronze discs set in the top. To help bind the top layer of concrete to the monument, two vertical reinforcing rods were left projecting above the lower portion. The bronze discs used were traverse station marks of the United States Coast and Geodetic Survey, with the legend ground off the tops. Monuments L and K are about one by two feet at the top and reach down to bed rock. A brass strip with two welded hooks was set in the top of each. The final center for each monument was set with a fine center punch in the bronze or brass. A large "O" steel die was used to cut a circle centered around the punch mark to set it apart from any other scratches made during preliminary work. All discs were stamped with the proper letter designation, and with the numbers, 1 to 17 (see Fig. 2), along the east-west lines beginning with the first monuments east of C and D.

Preliminary surveys--In order that the monuments might be set in their correct places, a preliminary survey was made with a BERGER seven-inch theodolite and a 300-foot steel tape. Locations L and K were spotted by projecting the rail lines out through the doors cut for the purpose. Wooden towers, 30 feet in height, were built over these locations to assure visibility from the ground at the east end of the present basin. This preliminary survey was conducted with an accuracy to meet the provision that the final points would fall somewhere near the center of the monuments. Even this required rough corrections for temperature and grade for distance measurements. Discs were set in the top of only monuments A, B, C and D at this time.

After the concrete monuments were set in place, a second preliminary survey was conducted to locate, with the necessary accuracy, the final positions of the bronze discs to be set in the top

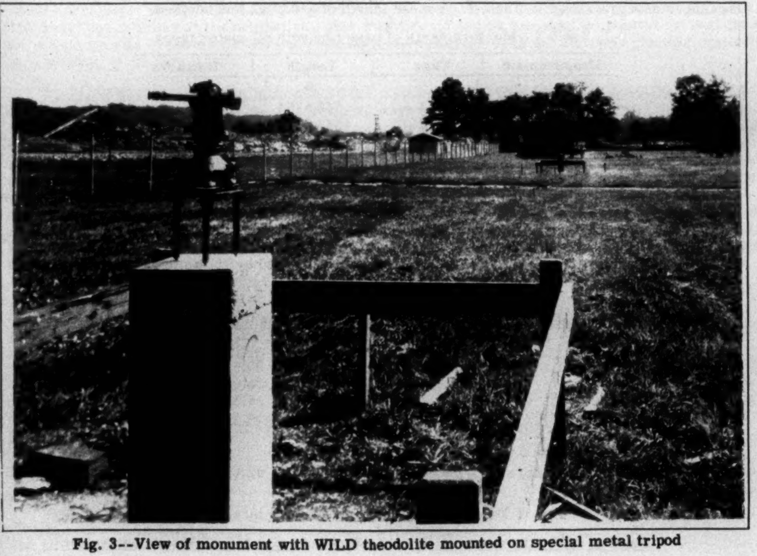

Fig. 3--View of monument with WILD theodolite mounted on special metal tripod layer of concrete. The line of track 3 was projected out to L with greater accuracy and the two east-west lines of monuments made parallel to it by equal tape measurements, north and south, from A and L. The locations for the discs along the east-west lines were determined by measurements with a specially standardized 120-foot invar tape. Rough wye leveling had been made over the top of the box forms used later to top off the monuments. Slope corrections were made during these measurements and nails placed in the side of the forms to designate the disc locations, both for distance and line. All discs were then finally set as well as the brass strips at L and K.

Standardization of tapes--As most measurements were to be made over monuments spaced 120 feet apart, it was decided to cut two old geodetic 50-meter invar tapes to the proper length, place a 120-foot mark on them, and calibrate the length as marked.

On fairly level ground, south of the present basin, an 1800-foot base was staked with four- by four-inch stakes braced both ways. This gave 15 tape lengths of 120 feet. Parallel to this and three feet away was staked a 550-meter base prepared in the same manner as the first except for measurement with 50-meter tapes standardized by the Bureau of Standards. These base lengths were selected for two reasons; first, they are of about the length over which precise measurements were to be made for the basin extension; second, for comparison purposes, the difference between the metric and foot distances is less than 1.5 meters. This minimized the "set-back" from 550 meters to 1800 feet that must be measured with a steel tape. Optical contact between the bases was made at each end by the following method.

A transit was carefully centered over the end of the 50-meter base and used to locate a second transit at right angles to the base about 100 feet away. The second transit was then used to transfer, optically, the position of the end mark of the 50-meter base to the position of the new end mark to be scratched for the 120-foot base. In this way, the use of a plumb bob was avoided. Duplication of this process indicated an error no greater than 0.2 mm. No effort was made to make the base any nearer 1800 feet than an amount measurable with a boxwood scale.

The 50-meter base was measured four times, employing the usual three support method. The measurements are shown in Table 1. A mean length of 548.5762 was adopted.

Table 1--Measurements of base line with 50-meter tapes

Measurement	Tape	Length	Remarks
		m	
1	554	548.5764	
2	917	548.5717	Rejected
3	554	548.5763	
4	917	548.5759	

This distance was then measured twice by each of two 120-foot invar tapes. In computing the lengths of these tapes, the adopted length of the base was held and the computation backed up to the only unknown, that of the correction to 120 feet for tape and catenary; that is, the correction to be applied to 120 feet to give the length of the tape when supported at 0, 60, and 120 feet, at 25° C under a tension of 15 kilograms. The corrections (multiplied by 15, as there were 15 tape lengths) derived from the measures are shown in Table 2.

Table 2--Corrections applied to measurements of base line with 120-foot tapes

Tape	Direction	Corrections
716	Forward	+ 30.6
716	Backward	+ 31.0
777	Forward	+ 14.3
777	Backward	+ 14.7

The final data on these tapes, supported at 0, 60, and 120 feet, under 15 kilograms tension, are shown in Table 3.

Table 3--Final data on 120-foot tapes

Tape	Length at 25°C	Expansion per 1°C	Weight per meter
			gms
716	120 ft + 2.05 mm	0.0157 mm per 120 ft	25.5
777	120 ft + 0.97 mm	0.0124 mm per 120 ft	25.5

The checks in the measurements were so small that a computed probable error would undoubtedly be meaningless. It is felt, however, that the lengths of these tapes were determined within a maximum error of 0.03 mm. All comparison measurements were made in one day. A single check measurement for each tape was made immediately after the survey work; no significant change was detected.

Rail projections--A ten-inch theodolite (BAUSCH and LOMB, No. 284), with a micrometer eye piece, was used in projecting the center lines of rails 3 and 1. The first problem was to project these lines onto the bronze discs set in monuments A and B. In the case of rail 3, the theodolite was centered over the rail about 1000 feet west of the east end of the rail. The center of rail was determined by the special device previously mentioned and the theodolite plumbed over it on a metal tripod with a plumb bob. The movable vertical cross hair of the micrometer eye piece was then set at the collimation point and the telescope pointed along the line of the rail, into the objective of a small transit centered over the rail about 50 feet distant (see Fig. 4). The position of the theodolite was then corrected by successive pointings, direct and reverse, of the transit between the centering device under the theodolite and the vertical cross hair. This is a rather tedious procedure, as the leveling of the large instrument and the pointing of its telescope had to be corrected every time it was moved. A track light, designed and built at the Model Basin, was set on the rail near the east end. This light (see Fig. 4, between the two instruments) clamps on the head of the rail and can be centered very accurately by a micrometer screw. The light can be seen through a vertical slit about 0.5 mm wide. In order that it might be seen over long distances, a diamond-shaped aperture, symmetrical with the vertical slit and about 1/2 inch across, was cut in the metal face. The two projection lights were of similar design, and fastened securely to a board. The distance between the vertical slits of these lights was about 295 mm. The lights were placed over the disc in monument A so that they straddled the rail line.

Small deflection angles were then measured with the micrometer eye piece of the theodolite between the track light and each of the projection lights. Ten sets of measurements, direct and reverse, were taken for each angle. No change in focus was necessary. The settings of the micrometer head were changed systematically to balance any error that might be introduced by variations in the micrometer screw. These settings were made symmetrical about the collimation axis. The position of the rail line at the projection lights was determined by a simple proportion derived from the measurements of the small left and right deflection angles. This position was plumbed optically, by a transit, to the disc itself.

The track light was then set back toward the west end of the basin and the theodolite centered optically over the point A. The projection lights were set on top of the tower over L, straddling the rail line, and the positions of the vertical slits plumbed down optically by transit to the brass strip on the monument. The procedure with the theodolite in this case was to point on the track light with telescope direct, transit the telescope, and measure the small deflection angles to the projection lights with the micrometer eye piece. The collimation error of the instrument enters directly into this single observation. The measurement was then repeated with the instrument reversed; the combined result constituted one set free from the error of collimation. Sixteen sets were taken using different parts of the micrometer screw as before. The plate levels of the theodolite were constantly checked. A striding level test indicated the standards to be in almost perfect adjustment and the pivots of the telescope to be very regular. The vertical angles to the lights in all cases were small; well under one degree. After the projection method was completed, directions were measured, by the usual method of 16 positions direct and reverse, from the track light to each of the projection lights. The combined results were used to calculate, as before, the position of the rail line between the two marks on the brass strip at L as plumbed down from the vertical slits of the lights on the tower. The same procedure was used on rail 1, except that the line to be projected here was defined by the center of the rail at two points only, stations 3 + 67.125 and 12 + 93.125. No change in focus was necessary. The observations were started just before sundown and extended into darkness. As a comparison between the projection and direction methods of line projection the following differences are given for each rail. These differences represent the divergences at the east ends (L and K) resulting from the two methods: Rail 3--direction method 0.1 mm south of projection method; Rail 1--direction method 1.3 mm south of projection method. The distance projected is 2108 feet. One second of arc is equal to about three mm at this distance.

Convergency of rails 1 and 3--It had always been known that rails 1 and 3 were not parallel. For this reason their lines were projected independently. As an over-all check, particularly on the effect of horizontal refraction, the writer suggested that the non-parallelism of the two rails

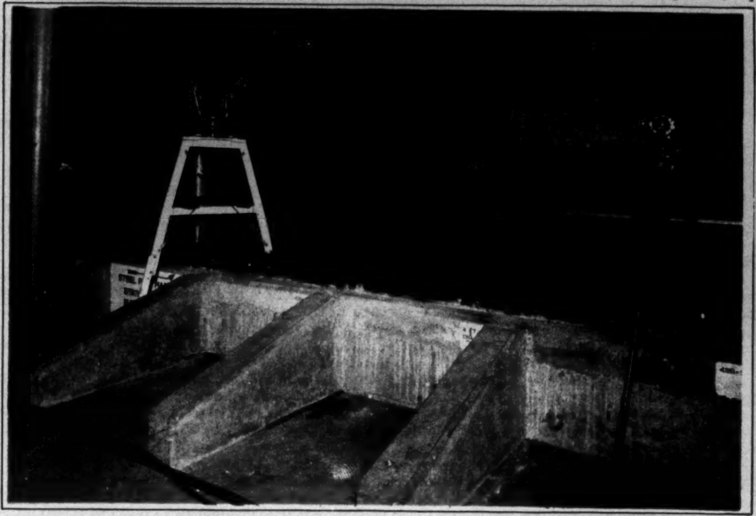

Fig. 4--View showing setup for centering large theodolite over rail

Fig. 5--Measuring the 120-foot station

be determined and applied to the observed results of the projections at the east end. Measurements between the rails at stations 3 + 67.125 and 12 + 93.125 with a standard 30-meter steel tape indicated that the rails converge to the east at a rate of 0.486 mm per 100 feet. Applying this to the distance measured between the lines as projected at the east end, a discrepancy of 4.8 mm developed; that is, the observed lines were too close together by this amount at the east end, according to the measured and calculated convergency.

Errors of projection--The probable error derived from the series of observations for the line projections probably would not exceed 1.0 mm. This takes into account only the accidental errors. It would be difficult to evaluate the systematic errors such as centering of the theodolite, plumbing from the 30-foot towers, lack of symmetry of the signal lights, etc. Any of these should not exceed 0.5 mm and probably are under 0.3 mm. However, as the projected line is more than twice the length of the existing track used in this work, any error in centering at the west end would be magnified at the east end. This also applies to the measurement of the convergency of the rails. Only a 926-foot length of rail could be used to test the convergency and the calculated convergency was extended 2300 feet. The systematic error which cannot even be estimated is that of horizontal refraction of light or the deviation of the line of sight from a straight line. Conditions on the site at the time of work indicated that it should be very small. After careful consideration it was decided to divide the discrepancy of 4.8 mm equally among the calculated convergency and the two line projections. There can be but little doubt that this adjustment eliminated, at least partially, the effect of the systematic errors, particularly that of lateral refraction. Accordingly, the final center punch marks were set in the brass strips, on L and K, 1.6 mm north and 1.6 mm south, respectively, from the originally observed points. From the theory of errors, the probable error of the mean of two measures (provided they result from a well-made series of observations) is equal to one-third the difference. Applying this to the case in hand, the probable error of the projected lines should not exceed 1.6 mm and might be considered smaller because of the adjustment due to the calculated convergence. This discussion is rather theoretical, but is about the only means we have of estimating the precision of the work without doing it all over and comparing the results.

"Squaring" the rectangular survey--To insure that the quadrilateral C-D-E-F would be as near a true rectangle (oriented with rail 3) as may be, the following method was employed. The distance of 176 feet was measured along rail 3 from the basic plug at station 12 + 64 to spot the distance for point A. Two 50-meter invar tapes and a standard 30-meter steel tape, supported throughout, were used for this purpose. The punch mark was set for the final position of A. With the use of a transit, scratches were made on the discs at C and D that formed an approximate right angle at A with rail 3. The theodolite was optically centered over the point at A by means of two transits about 90° apart. This took some time to do as can be imagined from a previous description of the work involved only in setting a theodolite on line. Small targets, consisting of a vertical pencil line on white paper tacked to a block of wood, were carefully centered over the scratches on the discs at C and D. The track light was centered over rail 3, at about the same distance from A as C and D. This was done to avoid changing of focus. Sixteen regular positions of the circle were taken for the directions of the targets at D and C from the track light on rail 3. The directions measured were 90° 00′ 15″.02 for D and 269° 59′ 58″.84 for C. The distances to D and C, already determined approximately, were 101.3 and 117.6 meters respectively. To correct the directions to 90° and 270° final punch marks were made 7.4 mm west of the scratch at D and 0.6 mm west of the scratch at C. The three points, A, C, and D, were now finally established. While the theodolite was still centered over A, point B was finally established at the intersection of the line to C and the center line of rail 1.

The same system was used at the east end. The theodolite was optically centered on the tower over the punch mark at L and directions taken from a slit light at A to targets over scratches on the the discs at E and F. This time the focus had to be changed, but it is believed any error due to change in focus was substantially cancelled in reversal of the telescope. Any important error in this connection would be evident in the range of the direction measurements. The directions measured here were 90° 00′08″.81 for E and 269° 59′55″.09 for F. To make these directions 90° and 270°, new scratches were made west of the old ones; 4.3 mm for E and 2.8 mm for F.

The distances A-D and A-C were then measured with 50-meter invar tapes. Odd distances were measured with a calibrated 5-meter interval and standard steel tape (No. 3479). The results of these measurements are given in Table 4.

The distances to temporary marks on E and F were measured from L. As a matter of fact, these distances were measured before the adjustment of 1.6 mm to the north of point L was made. The measurements between the temporary points are shown in Table 5.

Table 4--Measurement of distances AC and AD

Line AC			Line AD		
Tape	Distance	Remarks	Tape	Distance	Remarks
	m			m	
554	117.6079	Rejected	554	101.2456	
917	117.6061		917	101.2451	
554	117.6064				
917	117.6063				
Mean adopted	117.6063		Mean adopted	101.2454	

Table 5--Measurements of distances LE and LF

Line LE			Line LF		
Tape	Distance		Tape	Distance	
	Uncorrected	Corrected by 1.6 mm		Uncorrected	Corrected by 1.6 mm
	m	m		m	m
554	101.2490	101.2474	554	117.6201	117.6217
917	101.2485	101.2469	917	117.6200	117.6216
Mean adopted		101.2472	Mean adopted		117.6216

Relative elevations of the tape ends used in the slope corrections were determined with a geodetic level and a Philadelphia rod.

This completed the work necessary to set the final punch marks for E and F by correcting the above measurements by 1.8 and 15.3 mm to equal those of A-D and A-C. This was done and the corners of the rectangle were finally established. No final marks were punched without at least two, and usually three, men on the spot to check all measurements.

Measurements for 120-foot transverse monuments--Everything was thus prepared for the final measurements between the 120-foot transverse monuments along the two east-west lines. As stated previously, the starting points, C and D, are at station 14 + 40; the intervening monuments, numbered from 1 to 17, are at successive 120-foot stations from C and D; the east corner stations are about 68 feet beyond the number 17 monuments. The plan was to tape directly over the bronze discs set in top of the monuments, supporting the center of the tape in horizontal and vertical alignment with the ends. The middle support was one of a series of nails in a stick held vertically by one of the men. Alignment of this support was determined with the eye by the rear tape stretcher. The method of taping was that employed in our regular base line work (see Fig. 5). The tension and method of support used in the standardization of the special 120-foot invar tapes were duplicated. Elevation differences for slope corrections were determined by a geodetic level and Philadelphia rod.

The problem was somewhat different from that of measuring between two fixed points. While measuring the over-all distances D-E and C-F, it was necessary to spot 120-foot intervals as closely as possible along the route. This could have been handled by taping each interval, calculating the corrections to 120 feet and marking the discs as the work progressed. Over-all accuracy would have been sacrificed, however, due to an accumulation in errors resulting from the many small set-ups and set-backs as well as to the fact that the small corrections for temperature would never have been apparent for a single 120-foot interval. To get around these objections, this procedure was followed. Temporary crosses were scratched in each disc with a stylus. These were purposely set off center to keep clear of the final punch mark. The taping was conducted in the usual manner but, in addition, there was recorded the set-up or set-back to each temporary cross from the regular tape contact scratch. In this way these small measurements did not enter into the over-all picture and each one applied only to the monument on which it was made.

Final length reductions were made for distances from C and D to each successive temporary cross and the average corrections, resulting from all retained measurements, to each even 120-foot distance were listed for every monument. Four measurements were made on each line, two with each tape. One measurement on the south line was rejected.

The results of the over-all measurements are given in Table 6.

Table 6--Measurements along the lines of the 120-foot monuments

North Line, DE			South Line, CF		
Line	Tape	Distance	Line	Tape	Distance
		m			m
D to 17	716	621.8048	C to 17	716	621.8181
D to 17	716	621.8041	C to 17	716	621.8172
D to 17	777	621.7988	C to 17	777	621.8164
D to 17	777	621.8014	C to 17	777	621.8235 rejected[a]
D to 17	Mean adopted	621.8023	C to 17	Mean adopted	621.8172
17 to E	3479 mean	20.6947	17 to F	3479 mean	20.6799
D to E		642.4970	C to F		642.4971
Probable error 0.9 mm or 1:690,000			Probable error 0.3 mm or 1:2,100,000		

[a] This measurement was rejected principally because some of the data on intermediate monuments were in serious error.

The agreement between the measured lengths of the two lines (0.1 mm) was so close that no adjustment was necessary. It was naturally an accident that this agreement was as small as 0.1 mm. It indicates, however, that the means of squaring the survey were entirely adequate and that the length measurements are of a high precision beyond any doubt. The data on the intermediate monuments indicate that, without exception, the above errors become progressively smaller toward the west corners and that the errors for any individual 120-foot interval do not exceed about 0.2 mm. As an over-all guard against mistakes in the set-ups and set-backs to the final center punch marks, an extra taping was made from mark to mark on each line. No mistakes were discovered.

Before the final setting of punch marks could be made, alignment along the intermediate monuments was needed. Close alignment is not necessary here, but it was thought best to add this touch in case some unforeseen use might be made of it. A brief description of the method used follows. A small metal tripod, about ten inches high, was made in the Instrument Division of the United States Coast and Geodetic Survey to support a WILD theodolite directly on the monument (see Fig. 3). This theodolite was set on a monument near the middle of an east-west line and a slit light centered over the punch marks at both ends. The theodolite was purposely set slightly off the final line and the angle between the two slit lights measured four times, direct and reverse. The position of the theodolite was carefully noted by the relation between two fine scratches, one on the base of the instrument, and the other on the top of the metal tripod. The theodolite was then moved across the final line, its new position noted, and the new angle measured between the end lights. Each angle was of course near 180°, one a few seconds under, the other a few seconds over. By a simple proportion the correct position of the theodolite was determined and the instrument placed in line. The angle, which now should be 180°, was again measured and, when necessary, the position of the theodolite further corrected. This last correction was seldom necessary. The tripod, of course, remained stationary at all times. Now, with the instrument on line, final alignment was made on three or four monuments in each direction by pointing to the end lights. Enough sights were taken, with the telescope direct and reverse, on each monument to insure an accuracy of about 1.0 mm. Lines were scribed on the discs by a stylus and flexible rule. This operation was repeated until all monuments were taken care of. To avoid the use of a plumb bob entirely, lines on the monuments over which the theodolite had been set were taken care of by centering the instrument over one of its neighbors.

Rather than observe out of focus in alignment work at varying distances, the writer prefers to depend on the elimination of focusing error by an equal number of observations with the telescope direct and reverse. It is believed that, in a high grade internal focusing telescope, any exceedingly small error which might remain would be smaller than that introduced by the effect of parallax in observing out of focus.

With the scratches for alignment and the temporary crosses for distance, it was possible to set the final punch marks for each monument. A boxwood scale with a specially constructed right-angle arm was used to measure the final set-ups and set-backs. Four men were used to check these measurements before the final centers were set with the punch.

Determination of elevations--Differences of elevations were observed between the steel plug marker, described previously, and all of the monuments in the construction area. The elevation of this marker, 132.739 feet, was furnished by the Director of the Model Basin. Geodetic level no. G-85 and rod no. 324 were used in the observing program. A double spur line (one set up) was run from the steel plug to monument A. The observing then proceeded around the rectangle D-E-F-C and closed back on monument A. The error of closure on this loop was 1.0 mm. This error was adjusted around the loop, nearly two km in length, and all elevations computed in relation to that furnished for the steel plug marker. Since elevations were needed for each monument, it was decided, in the interest of precision, to set the level half way between successive monuments and observe the elevation differences over short sights. By the time the leveling was commenced it was rather difficult to get into the line of the monuments at places. For this reason the differences were observed twice between monuments before moving on. The order of the sights was reversed on the second observation. If a difference exceeding 0.8 mm developed, additional observations were taken. Generally this difference did not exceed 0.5 mm. Only one rod was used to avoid any uncertainty of index error. It is fair to assume that none of the relative elevations exceeds 1.0 mm, well within the tolerance specified. Two additional Coast and Geodetic Survey bench marks were set in the steps to the present administration building, and these, as well as the monuments in the construction area, were tied into the general sea-level net in the vicinity.

Additional leveling was done along the tops of the four rails within the present basin. Elevations were determined at stations about 128 feet apart. Loops were formed by running between the rails at both ends. The maximum loop closure was 1.1 mm, but most of them were well under this. In the interpretation of the results it is difficult to say whether the small differences developed for each rail (0.002 or 0.003 foot) should be attributed to actual differences of elevation of the rail or to errors in the level observations.

Distance between basin rails--The distances between the center lines of rails 1 and 2 and between the center lines of rails 3 and 4 were measured at stations 128 feet apart along the present basins. Standard 30-meter steel tape no. 3479 was used for this purpose. The center lines of rails 1 and 3 were accurately determined by the special clamp device. The center lines of the other rails had to be estimated with a boxwood scale, as they are not of the same width. The results of these measurements indicate a variation of 0.005 or 0.006 foot for each pair of rails. The mean of all measurements for rails 1 and 2 was 52.652 feet and for rails 3 and 4, 22.658 feet.

The purpose of these measurements was to determine means by which the lines of rails 2 and 4 could be established in the construction area from the accurately projected lines of rails 1 and 3. When the time arrived for this, the writer pointed out that it would be difficult to reproduce these measurements with other than the tape used in the basin, under the same method and somewhere near the same temperature. The following method was suggested and is now being used. One of the 120-foot invar tapes was taken into the basin and stretched under 30 lbs tension across each basin. One of the end marks was placed in contact with the center of one rail, and a fine scratch made on the tape at the center of the other rail, corrected for the average distance between the rails. The tape was marked for each gauge and carried into the construction area and used with complete confidence. The maximum error from temperature changes can not exceed 0.3 mm, a negligible amount.

Conclusion--With the monuments and their coordinates as established, it is relatively a simple problem to carry elevation, distance, and alignment into the construction area with ordinary surveying equipment. The only exception to this is the establishing of the rail lines near the center of the extended basins. For this reason, the writer has helped at various times in this respect. The WILD theodolite and the method employed in alignment of the side lines were used for this purpose. It is much easier to interpolate points between fixed stations than to extrapolate points outside fixed stations. When the building is completed, it is believed that, under cover and ideal conditions, optical alignment can be obtained for the entire 3100 feet within 0.5 mm or better. Of course extreme care, the best of equipment, proper procedures, and many observations will be necessary.

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RELATIONS BETWEEN SOLAR ACTIVITY AND THE LOWER ATMOSPHERE

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The existence of close connections between solar activity and physical processes in the upper atmosphere, such as auroras, magnetic storms, and ionospheric variations is well established. Whether similar relations exist between solar activity and the state of the lower atmosphere is an open and sometimes hotly debated question. Solar energy is universally considered as the driving power of the atmospheric engine. However, many meteorologists feel that the observed changes of the solar constant, even if they are real and not only caused by changes of atmospheric transparency, are too small to produce any noticeable changes in the atmospheric circulation.

It would seem that if a plausible mechanism were suggested for the interaction between the Sun and the lower atmosphere this idea would become much more acceptable to the majority of meteorologists. For this reason the outline of a hypothesis is presented here, which links the two phenomena. Observational information for a quantitative discussion is largely lacking. The purpose of this note is to start discussion of the subject, and to show what kind of investigations are required to check the hypothesis.

Since terrestrial observations of the solar constant show only slight variations of doubtful reality, the changes of the Sun's energy which affect the atmosphere must be of such a nature that the observed solar constant remains nearly the same. MARIS and HULBURT [1929] have considered this possibility in connection with a theory of auroras and magnetic storms. They assume that a small part of the Sun's surface, say 1/10,000, raises its temperature suddenly to a much higher value. Such a region of high temperature on the Sun will be referred to as a solar flare. It seems likely that these flares are connected with the prominences which appear frequently on the Sun. To have a specific case in mind as an illustration, it may be assumed that the effective temperature in the region of such a solar flare increases from the ordinary 6,000° K to 30,000° K. Supposing that the Sun radiates as a black body even in the ultraviolet, a solar flare would increase the total energy output of the Sun by somewhat more than six per cent. Radiation, whose wave length is shorter than about 3,000A, is absorbed by ozone and other atmospheric gases in the high atmosphere, so that only radiation longer than 3,000A arrives in the troposphere. In this long-wave part of the spectrum the energy would only increase by about 0.7 per cent. This figure is of the same magnitude as the observed variations of the solar constant. It is immaterial here whether these variations are real or caused by errors in the observation technique. In either case the observations do not contradict the assumptions about solar flares. On the other hand, the energy increase in the ultraviolet region would be very large. In the case considered here, it would increase 2.45 times, provided that the Sun radiates like a black body in the ultraviolet. It must be added that the deviation of the solar radiation from that of a black body is probably very large in the ultraviolet, as shown by ionospheric observations, for instance. Nevertheless, it is at least apparent from the foregoing figures, that large changes of the solar energy emission may occur without showing themselves in the solar constant as determined at the Earth's surface.

The absorption of the additional energy produced by a solar flare must cause marked changes in the upper atmosphere. Apart from the variations in ionization, clearly reflected in the radio fadeouts, appreciable rises must also occur in the temperature of the high atmospheric layers. The ionospheric temperature changes presumably have no appreciable effect on the lower atmosphere, especially on the troposphere, because of the small total mass of the ionosphere. But even in the ozone layer, between 20 and 40 km, approximately, very substantial temperature increases must take place, although a considerable part of the ultraviolet energy is absorbed above the ozone layer. The temperature rise is very rapid and may be accomplished in something like half an hour. MARIS and HULBURT [1929] estimate that the temperature at 40 km will rise from 280° to 390°K, while at 20 km it will rise only from 228°K to 230°K. At these levels the atmospheric pressure is still appreciable, compared to that at the ground, about 55 mb at 20 km, and 5 mb at 40 km. Hence, ozonospheric variations induced by solar flares will make themselves felt at the Earth's surface, and it is suggested that the ozonosphere represents the missing link between solar activity and tropospheric phenomena.

The heating effect of a solar flare can hardly be the same everywhere in the ozonosphere. Even if ozone were distributed uniformly, the latitudinal differences of the incoming solar energy, caused by the different solar altitude, would produce stronger heating at low latitudes than at high latitudes. But it must be kept in mind that other factors, perhaps very localized ozone clouds, may bring about similarly localized temperature anomalies. Even if such ozone concentrations do not exist, the temperature distribution will not depend on the latitude alone, because the heating effect is confined to the day hemisphere. However, for the sake of brevity, only the case of the temperature distribution as a function of the latitude will be considered here.

If it is assumed that the mean temperature of the air column between 20 and 40 km over the equator increases 50°K (in agreement with the quoted example), while it remains unchanged at the poles, a strong pressure gradient develops in meridional direction above 20 km elevation. At 30 km, for instance, the acceleration caused by this pressure gradient would be 0.2 cm/sec^2. This pressure gradient alone would not cause any variations of the pressure distribution below 20 km. But, because of the pressure gradient, the air in the ozonosphere will begin to move, at first in the direction to the lowest pressure, that is, toward the poles. This direction of motion is changed by the CORIOLIS force which acts normal to the velocity vector. Because of the stable stratification of the ozone layer, the motion must be essentially horizontal, and therefore only the horizontal component of the CORIOLIS force needs to be considered. A particle of air starting out with a purely meridional component of motion is deflected so that it acquires a zonal velocity component. This zonal component of the velocity produces a component of the CORIOLIS force towards the equator that is in the direction opposite to the original, thermal, pressure gradient. In order to estimate the possible pressure changes in the lower atmosphere, it may now be assumed, tentatively and rather arbitrarily, that the motion of the particle becomes purely zonal when the equatorward component of the CORIOLIS force equals the pressure-gradient force directed towards the pole. Since the horizontal component of the CORIOLIS force increases as the sine of the latitude, a particle starting at low latitude will travel through a greater latitudinal distance than a particle starting out at a higher latitude, where the CORIOLIS force is stronger. This fact, together with the convergence of the meridians towards the poles, will result in divergence near the equator and strong convergence at tropical and subtropical latitudes. At higher latitudes the convergence decreases and becomes unimportant, since the meridional displacement becomes very small. Below the regions in the ozonosphere where divergence takes place the pressure will fall; where convergence occurs the pressure will rise. With the figures for the heating of the ozonosphere assumed previously, the pressure at 20 km elevation between 20° and 30° latitude would rise by about 20 mb. Since this figure represents an actual mass increase over the region, its full value will make itself felt at the ground.

Actually the resulting pressure changes will presumably be smaller than the figure just quoted. This is indicated by the fact that the diurnal barometer oscillations are rather small, even though a large diurnal temperature variation should exist in the ozonosphere. The pressure changes at sea level, caused by solar flares, will be larger than these diurnal variations, because the ultraviolet energy output increases much more with the eruption of solar flares than from night to day.

Theoretically, it can also be surmised that the effects will not reach magnitudes of the order of 20 mb. The whole picture of the thermally induced motion in the ozonosphere is very crude, and should be replaced by a more refined analysis. Even disregarding the differences between the heating of the day and night hemispheres, it can hardly be expected that an air particle will move in a purely zonal direction, as soon as the meridional component of the CORIOLIS force acting on it is equal to the original meridional pressure gradient. Actually the meridional component of velocity is at that moment still considerably larger than the zonal component, so that the air may move farther poleward, thus increasing the divergence near the equator and the convergence at higher latitudes. On the other hand, the meridional motion of the air reduces the original thermally produced pressure gradient. The effect of this reduction of the pressure gradient on the motion has not been considered at all here. If it is taken into account, the horizontal displacements will be reduced substantially. It is necessary to solve rigorously the hydrodynamic problem which arises out of the suggested heating of the ozonosphere, in order to get a clearer idea of the motions which can be expected. But the simple picture of the ozonospheric circulation visualized here shows that solar flares may produce appreciable changes in the lower atmosphere.

The outline of the hypothesis presented here is necessarily rather vague, and in addition to the problem just mentioned, namely, the motions in the ozonosphere, a number of other questions will have to be studied in order to put the hypothesis on a firmer basis. The first of these problems concerns the solar flares. Obviously not every solar flare will cause the required changes in the atmosphere. Presumably, as in the case of the radio fade-outs, the solar flare must have a certain minimum temperature and minimum area if appreciable effects are to be observed in the troposphere. It may also be necessary that the flare persists at least for a certain length of time.

In the second place, the amount of heating produced in the ozonosphere by solar flares will have to be investigated more thoroughly. It appears likely that the solar flare does not only cause temperature rises but also changes of the ozone content. If this is true, the temperature will be different from that computed under the assumption of a normal ozone distribution. In addition to these theoretical studies, observations of the temperature of the ozone layer will be desirable up to at least 40 km, in order to show the actual occurrence of large temperature rises caused by solar flares.

As far as the effect on the lower atmosphere is concerned, no very definite statements can be made before the ozonospheric motions have been analyzed more completely. All that can be asserted, at present, is the likelihood of appreciable pressure variations at the ground produced by solar activity. Such pressure variations must be accompanied by substantial motions of the air in the troposphere and the resulting meteorological phenomena. It is, of course, feasible to make an attempt to establish connections between solar phenomena and the lower atmosphere directly by statistical studies without any theoretical concept of the mechanism linking the Sun and the atmosphere. However, such a procedure would require a large amount of wasted effort, since at present neither the solar cause nor the atmospheric effect is definitely known. After the theoretical investigations have progressed to a more definite state, statistical checks of the relations indicated by theoretical reasoning will be very necessary.

In concluding, it may be remarked that the hypothesis outlined here will have been of some value even if further study proves it to be untenable, because in that case it is difficult to see how any causal relationship between solar activity and weather can exist. On the other hand, it is well to keep in mind that the establishment of relations between solar activity and the lower atmosphere on a firm physical basis cannot be expected to bring about a complete solution of the problem of weather forecasting. The solar flares would be only one of the factors influencing the atmosphere, and, moreover, the atmosphere will respond differently to the same impulse, depending on its initial state. Nevertheless, considerable progress in the understanding of atmospheric developments can be expected, if one more of the causes of atmospheric changes is found.

This study was undertaken by the author as Abbott Lawrence Rotch Research Fellow at the Blue Hill Meteorological Observatory of Harvard University at the request of C. F. BROOKS, Director.

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GAUSS' METHOD OF MEASURING THE HORIZONTAL COMPONENT OF THE EARTH'S MAGNETIC FIELD, A DISCUSSION OF FUNDAMENTALS IN THE LIGHT OF THE ACTIONS OF THE INTERNATIONAL ELECTROTECHNICAL COMMISSION

Frank Wenner

Abstract -- This paper makes use of a discussion of Gauss' method of measuring the horizontal component of the Earth's magnetic field as a means for presenting those ideas concerning the natures of magnetic quantities which have been promulgated by the International Electrotechnical Commission. Reference is also made to the actions taken or initiated by the International Electrotechnical Commission (hereafter abbreviated IEC) relative to the fundamentals of measurements of mechanic, electric, and magnetic quantities.

Any quantity has a magnitude independent of the magnitudes of other quantities of the same nature. For example, the length of a particular table does not depend on the length of some box or the length of some measuring stick. That is, the magnitude of a particular physical quantity is the same regardless of the number used to express this magnitude.

In a piece of soft iron there may be an induction, B, and if so it may be presumed that this results from a cause which is called the field or intensity, H. These are quantities of different natures so it cannot be said that they have the same or different magnitudes. This statement is applicable when the induction is in air or in a vacuum as well as when it is in soft iron. Furthermore, the induction, B, depends not only on the intensity, H, but also on the permeability, P, of the material or medium in which the induction occurs. According to the ideas promulgated by the IEC the energy density resulting from an induction in a magnetically soft material or medium may be considered to be either $BH/8\pi$, $PH^2/8\pi$, or $B^2/8\pi P$. From these energy density relations it follows that

$$B = PH \qquad (1)$$

Since B and H represent quantities of a different nature for equation (1) to be valid, it is necessary that P represent not a numeric but a quantity of such nature that the product of this quantity and the intensity be of the nature of an induction.

In discussing the torques acting on a magnet when placed in a magnetic field, it is necessary to introduce some sort of working hypothesis. As a first hypothesis, let it be assumed that the swinging magnet as used in Gauss' method acts as though it were a coil of insulated wire having in it a sustained current. If, then, I is the current, A, the area, and N, the number of turns, the magnetic moment is

$$M = IAN \qquad (2)$$

Let K represent the moment of inertia of this magnet and T represent its period when swinging freely in the Earth's magnetic field. Then, according to the IEC, most electrical engineers, some physicists, and a very few geophysicists

$$T = 2\pi\sqrt{K/MB} \qquad (3)$$

Here B represents what the horizontal component of the induction would be at the point in question, provided the magnet were removed to a great distance. From equation (3) it follows that

$$MB = 4\pi^2K/T^2 \qquad (4)$$

Referring now to the second part of the measurement by Gauss' method it is to be noted that a current in a coil of wire produces in the direction of its axis and at distances, R, large relative to the dimension of the coil an intensity

$$H' = \pm 2AIN/R^3 = \pm 2M/R^3 \qquad (5)$$

In case the coil (magnet) instead of being permitted to swing in the Earth's magnetic field is so located as to make the induction at the point in question zero it follows that

$$H + H' = 0 \quad \text{. . . . . } (6)$$

where H represents the horizontal component of the Earth's intensity with reference to the point in question. From equations (5) and (6) it follows that

$$H/M = 2/R^3 \quad \text{. . . . . } (7)$$

and from equations (4) and (7) it follows that

$$BH = 8\pi^2 K/T^2R^3 \quad \text{. . . . . } (8)$$

As a second hypothesis let it be assumed that the swinging magnet used in Gauss' method acts as though it were a large number of dipoles, oriented mainly in the direction of the length of the magnet. Then, according to the ideas usually presented in text books

$$T = 2\pi \sqrt{K/MH} \quad \text{. } (9)$$

From equation (9) it follows that

$$MH = 4\pi^2 K/T^2 \quad \text{. . . . . } (10)$$

Referring now to the second part of the measurement by Gauss' method it is to be noted that the process of magnetizing the magnet results in an induction outside as well as within the magnet. At distance large relative to the dimensions of the magnet and in the direction of the length of the magnet that component of the induction resulting from the magnet

$$B' = \pm 2M/R^3 \quad \text{. . . . . } (11)$$

In case the magnet instead of being permitted to swing in the Earth's magnetic field is so located as to make the induction at the point in question zero it follows that

$$B + B' = 0 \quad \text{. . . . . } (12)$$

So

$$B' = -2M/R^3 \quad \text{. . . . . } (13)$$

Therefore

$$B/M = 2/R^3 \quad \text{. . . . . } (14)$$

From equations (10) and (14) it follows that

$$HB = 8\pi^2 K/T^2R^3 \quad \text{. . . . . } (15)$$

Thus, either of the hypotheses used leads to the conclusion that both the induction and intensity are involved and that these are involved as a product.

From equations (1) and (8) or (15) it follows that

$$B = (2\pi/T)\sqrt{2KP/R^3} \quad \text{. . . . . } (16)$$

and

$$H = (2\pi/T)\sqrt{2K/PR^3} \quad \text{. . . . . } (17)$$

To this point we have been concerned with the establishment of ratios of magnitudes of quantities of like nature. In each of the equations considered above the symbol or combination of symbols to the left of the equality sign and the symbol or combination of symbols to the right of the equality sign represent two quantities of the same nature. Furthermore, the magnitudes of these quantities have the ratios indicated by the numerics appearing in the equations. For example, in equation (13) M/R^3 represents an induction the magnitude of which is half the magnitude of the induction, B'.

In arriving at equations (16) and (17) use has been made only of well-known laws of physics interpreted in the light of the actions of the IEC. No reference has been made to standards of quantities represented by individual symbols or combinations of symbols. Neither has any reference been made to units of the quantities. However, if equations (16) and (17) are to be used in arriving at results in forms such that they can be entered in a record it is necessary that the quantities represented by the symbols P, T, K, and R be measured by direct or indirect comparison with an appropriate set of standards. Should the standards used be those of length, mass, time, and permeability--namely the basic quantities of the electromagnetic system of measurements--the horizontal component of the induction, B, and the horizontal component of intensity, H, will have been measured as quantities of the electromagnetic system of measurements.

The IEC proposed two sets of units for use with the electromagnetic system of measurements, both of which are defined in terms of the same standards of length, mass, time, and permeability. In one of these the unit of permeability is defined as the permeability of free space. In the other of these the unit of permeability is defined as 10^7 times the permeability of free space. In using Gauss' method the ambient medium is air which, for all practicable purposes, may be considered to have a permeability the same as the permeability of free space. Consequently the numerical value to be assigned to the permeability will be either 1 or 10^{-7} depending on which of the systems of units is to be used. For one of the systems of units the numerical values to be assigned to the intensity and to the induction will be the same. For the other system of units the numerical value to be assigned to the intensity will be 10^7 times the numerical value to be assigned to the induction B.

In the system of units in which the unit of permeability is 10^7 times the permeability of free space, the unit of length is the meter, the unit of time is the second, and the unit of mass is the kilogram. This, according to the recommendations of the IEC, should be called the Giorgi system of units. The so-called fourth unit of the Giorgi system, namely, the unit of permeability, was adopted at Torquay in 1938, but presumably this action has not been confirmed as yet.

In the system of units in which the unit of permeability is the permeability of free space, the unit of length is the centimeter, the unit of mass is the gram, and the unit of time the second. The IEC adopted names and abbreviations or symbols for the names of most of the magnetic units of this system. Among others they adopted: Gs as an abbreviation or symbol for gauss, the name of the unit of induction; and Oe as an abbreviation or symbol for oersted, the name of the unit of intensity--the quantity which they call magnetic field strength. They did not adopt a name for either of the units of permeability. This is but one of many indications that the job on which they and others labored so long and so faithfully has not been carried to a satisfactory conclusion.

Electric and magnetic magnitudes and units have long been subjects of controversy. What the IEC apparently was aiming at was a clarification of ideas concerning such matters and the establishment of physical measurements on a more satisfactory basis. In these aims they sought and received the cooperation of the Symbols Units and Nomenclature Committee of the International Union of Pure and Applied Physics and the Comité Consultif de l'Electricité of the International Commission of Weights and Measures. Through these organizations, efforts of the individual delegates of the IEC and others, there was secured the cooperation of the International Bureau of Weights and Measures and of the national standardizing laboratories of various countries.

Aside from promulgating the idea that induction and intensity are of different physical natures, and the adoption of the Giorgi system of units, the IEC rather indirectly proposed:

(1) The adoption of the electromagnetic system of measurements as a fundamental system of measurements. In this system all units are, in effect, defined in terms of standards of length, mass, time, and permeability.

(2) The recognition that, for the purpose of classroom instruction, units may be selected solely on the basis of convenience. Since in neither classroom demonstrations nor in assigned problems is it necessary to bring forth any standards, it is permissible to use an isolated magnet pole or pair of such poles as one of the standards of a system of measurements. In that case the units may be defined in terms of this standard, and standards of length, mass, and time--as is usually done. Likewise, it is permissible to use an ohm, an ampere, a volt, a henry, a farad, a coulomb, or a weber as the fourth fundamental unit of a system of units. In that case all units except fundamental units may be defined in terms of this and three additional fundamental units. It is not necessary that any of the units selected as fundamental be defined, nor, if defined, is it necessary that their definitions bear any similarity to definitions actually used in national standardizing laboratories.

(3) The adoption of the presently used international system of measurements as a working system of measurements. Here all units are in effect defined in terms of standards of length, time, electromotive force, and resistance. This system, more than any other, is now used directly or through the calibration of pointer-type instruments in measurements of electric and magnetic quantities.

(4) The establishment of new definitions for the units of the international system of measurements in terms of standards of this system of measurements in such a way as to be in accord, to a high accuracy, with the units defined in terms of the standards of the electromagnetic system of measurements. The purpose of this is to make it possible to use indiscriminately the standards of these two systems of measurements, not only for ordinary accuracies, as is now being done, but also for very high accuracies.

Proposition (4) involves measurements of two quantities, such as induction and intensity or current and inductance, as quantities of the working or international system of measurements and also as quantities of the electromagnetic system of measurement. In either case the mass represented by the standard of mass and the permeability represented by the standard of permeability of the electromagnetic system of measurements will have been measured as quantities of the international system of measurements. Also the electromotive force of the standard of electromotive force and the resistance of the standard of resistance of the international system of measurements will have been measured as quantities of the electromagnetic system of measurements. Such measurements require laboratory facilities and the use of standards of length, mass, time, permeability, electromotive force, and resistance.

Nothing need be said here concerning standards of length, mass, or time and nothing further need be said concerning a standard of permeability. During the interval between World War I and World War II investigations made in national standardizing laboratories led to marked improvements in standards of electromotive force and to marked improvements in standards of resistance. Therefore, reasonably satisfactory standards for both of these systems of measurement were available. Also, during this interval, investigations made in national standardizing laboratories led to marked improvements in methods and the quality of the apparatus used in the measurements serving to give the magnitudes of the electromotive forces represented by the standards of electromotive force and the magnitudes of the resistances represented by standards of resistance in terms of units defined in terms of standards of the electromagnetic systems of measurements. Such measurements were being made in some of the national standardizing laboratories and reasonably satisfactory results had been obtained by the end of 1938.

From time to time the standards of electromotive force and standards of resistance of the various national laboratories had been intercompared at the International Bureau of Weights and Measures. A further such intercomparison was to have been made during 1939. On the basis of the results obtained in this intercomparison, and the results obtained in the measurements made in the national standardizing laboratories of the various countries, the units of electromotive force and of resistance for each country were to have been defined in terms of its own standards of electromotive force and of resistance. As of January 1, 1940, the units so defined were to have replaced the presently used international units of each country.

Here an attempt has been made to give an inkling as to the present status of the fundamentals of measurements of mechanic, electric, and magnetic quantities. The subject which has been considered is of a highly controversial nature. It is not surprising, therefore, that some look upon the actions taken and initiated by the IEC as leading the way to a better understanding of the fundamentals of physical measurements and to the establishment of physical measurements on a much more substantial basis, while others look upon these actions as showing an utter lack of comprehension of matters "entirely too elementary to be the subject of discussions and votes at learned international congresses."

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REFRACTION OF WATER WAVES BY ISLANDS AND SHOALS WITH CIRCULAR BOTTOM-CONTOURS

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(Contribution from the Scripps Institution of Oceanography, New Series, No. 282. This paper was prepared in June, 1945, in connection with wave research carried out for the Navy Department, Bureau of Ships, under contract NObs 16290.)

Abstract--The bending of water waves by islands and shoals with circular bottom-contours is investigated from an analytical standpoint to obtain a precise determination of resulting wave-patterns and wave-heights. SNELL'S law of refraction is assumed, and FERMAT'S law or the principle of least time therefore applies. Application of FERMAT'S law and of the established relation between wave-velocity and depth of water enables determinations of lines orthogonal to the wave crests for various types of contour gradients. Five different cases are discussed. It is shown that for certain contour gradients, islands have no shore protected from high waves. A shoal is characterized by the dividing of a single crest into two crests. Height variation along refracted crests at considerable distances beyond an island is shown to be critically dependent upon contour gradient.

Introduction

Wave-crests approaching a shore line at an angle are bent because the velocity of the wave in shallow water decreases as the depth decreases. The portion of a crest first reaching shallow water is retarded most, and bending results. The process is similar to optical refraction, and follows SNELL'S law of refraction. Such refraction causes a change in wave-height as well as a change in direction of travel. The change of height can best be determined by consideration of a network of lines everywhere perpendicular to the wave-crests. These lines are referred to as the orthogonals. The wave-energy between two orthogonals can be considered to remain constant. If orthogonals diverge, wave-energy per unit crest-length decreases. The wave-height, which is proportional to the square root of the energy, likewise decreases. The opposite is true when orthogonals converge.

The usual problem is one of constructing a "refraction" diagram showing the orthogonals which result from known bottom-contours and initial wave characteristics. Changes in wave-height and direction of travel caused by refraction can then be determined from the orthogonals.

These orthogonals associated with refracted waves can be found by graphical methods which are discussed by the Beach Erosion Board [U. S. Engineer Department, 1942, see "References" at end of paper]. Detailed instructions for drawing such refraction diagrams are given in Hydrographic Office Publication 234 [1944, pp. 31-34]. The preparation of these diagrams is time consuming, and, for certain critical conditions, it is very difficult to obtain the desired accuracy. On the other hand, an analytical solution for the orthogonals gives very accurate results, but has the disadvantage that the variation in depth must be expressed by means of an analytic function.

For the case of straight parallel depth-contours an analytical solution can be found from SNELL'S law [H.O. 234, 1944, p. 7]. For cases of concentric circular contours a solution can be found by the application of FERMAT'S principle. Solutions for several of these cases are given in this paper. They show that under certain conditions the wave-heights on the lee shore of an island can be quite high and that islands do not necessarily offer a zone of protection in their lee. These conclusions are in agreement with a number of observations, but it had been thought that an explanation would have to be based upon wave diffraction.

The method developed in this paper is, of course, no substitute for drawing refraction diagrams, but the results shown here will help in drawing diagrams for islands and in evaluating the refraction effect of islands at large distances.

Application of FERMAT'S law

FERMAT'S law states that light will travel in a path such that the travel-time is minimum [JOOS, 1934, pp. 381-382]. The proof of FERMAT'S law depends upon SNELL'S law (law of refraction). SNELL'S law has been found to be valid for water waves in shallow water, and therefore

FERMAT'S law is valid. Consequently the problem is one of determining the path between two points, such as P_0 and P, which makes the following integral of (1) have a minimum value.

$$I = \int_{P_0}^{P} (C_0/C)\, d s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In the above integral C_0 is the deep-water wave-velocity which can be assumed constant, C is the variable wave-velocity along the path, and d s is the arc length along the path. The minimizing path is an orthogonal, and the method of the calculus of variations can be used to obtain the equation of the orthogonal. When the bottom-contours are assumed to be concentric circles, it is desirable to introduce polar coordinates as shown in Figure 1. The above integral takes the form

$$I = \int_{\theta 0}^{\theta} (C_0/C) \sqrt{r^2 + (r')^2}\, d\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $r' = dr/d\theta$

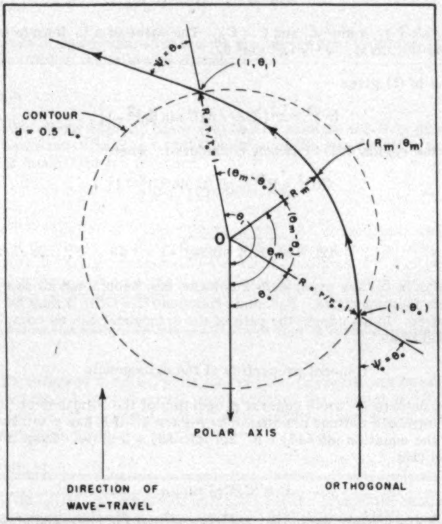

Fig. 1--Polar-coordinate representation of an orthogonal associated with wave-crests

The following initial conditions are to be satisfied: (1) $C = C_0$ for $r = r_0$; (2) a given orthogonal passes through point (r_0, θ_0); (3) a given orthogonal is parallel to the polar axis of the polar-coordinate system at point (r_0, θ_0).

Application of the method of the calculus of variations leads to the EULER-LAGRANGE condition [JOOS, 1934 ,pp. 68-70] as given in (3).

$$\frac{d}{d\theta}(\partial F/\partial r') - (\partial F/\partial r) = 0 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where $F = (C_0/C)\sqrt{r^2 + (r')^2}$.

The equation, $r = r(\theta)$, of any path which minimizes the above integral must satisfy (3). This differential equation is a necessary condition, and for many problems is a sufficient condition. Sufficiency of the condition will not be investigated here.

The assumption of circular bottom-contours means that the wave-velocity, C, is a function of r only, and that F is a function of r and r′ only. Under such conditions (3) may be integrated once without specifying the exact form of F. It may be verified by substitution that a solution of the equation (4) is a solution of (3).

$$F - r'(\partial F/\partial r') = a \quad \ldots\ldots (4)$$

Substitution of the expression for F gives

$$(r')^2 = r^2[(C_0 r/aC)^2 - 1] \quad \ldots\ldots (5)$$

The constant of integration, a, can be determined from the initial conditions. If Ψ is taken as the angle between the radius vector and the tangent to the orthogonal $r = r(\theta)$, then

$$\sin^2\Psi = r^2/[r^2 + (r')^2] \quad \ldots\ldots (6)$$

At the point (r_0, θ_0), $\sin^2\Psi_0 = \sin^2\theta_0$ and $C = C_0$. The value of a is determined by these initial conditions and (5) and (6); thus, $a^2 = r_0{}^2 \sin^2\theta_0$.

Substitution for a in (5) gives

$$(r')^2 = r^2[(C_0 r/r_0 C \sin\theta_0)^2 - 1] \quad \ldots\ldots (7)$$

Let $R = r/r_0$ where the region $0 \leq R \leq 1$ is now considered. Then

$$(R')^2 = R^2[(C_0 R/C \sin\theta_0)^2 - 1] \quad \ldots\ldots (8)$$

Finally

$$dR/R\sqrt{(C_0 R/C \sin\theta_0)^2 - 1} = \pm\, d\theta \quad \ldots\ldots (9)$$

Since the variables in (9) are separated, a solution can be obtained as soon as the variation in wave-velocity, C, with R is specified. For some functions $C = C(R)$ it may be necessary to resort to numerical integration. In all cases, the path of the orthogonal can be completely determined by (9) and the initial conditions.

General properties of the orthogonals

It is desirable to determine some general properties of the solutions of (9) before solving for specific cases. The symbols defined are shown in Figure 1. If R has a minimum value, R_m, it will be a solution of the equation $(dR/d\theta) = 0$. Set $(dR/d\theta) = 0$ in (9). Then if $0 < R_m < 1$, R_m will be a solution of equation (10).

$$R = (C/C_0)\sin\theta_0 \quad \ldots\ldots (10)$$

Suppose that such a minimum value, R_m, exists and that the corresponding value of θ is θ_m. The orthogonal starts at point $R = 1$, $\theta = \theta_0$ at which $(dR/d\theta)$ is negative since R is decreasing with increasing θ. The solution of (9) with negative sign gives the equation of the orthogonal from $R = 1$, $\theta = \theta_0$, to $R = R_m$, $\theta = \theta_m$. At the latter point $(dR/d\theta) = 0$. Since R increases with increasing θ from this point on, the positive sign must be used in (9). R continues to increase with increasing θ until again $R = 1$. Suppose $\theta = \theta_1$ when again $R = 1$.

By integrating (9) with proper choice of sign it is possible to obtain θ_m and θ_1. Let J represent the integral of the left-hand side of (9). Then from (9) with negative sign

$$\theta_m = \theta_0 + [J]_{R_m}^{1} \quad \ldots\ldots (11)$$

Similarly, from (9) with positive sign

$$\theta_1 = \theta_m + [J]_{R_m}^{1} = \theta_m + (\theta_m - \theta_0) \quad \ldots\ldots (12)$$

If Ψ_1 is the angle between the radius vector and the tangent to the orthogonal at $R = 1$, $\theta = \theta_1$, then by (6), (8), and the initial conditions

$$\sin^2\Psi_1 = 1/[1 + (\csc^2\theta_0 - 1)] = \sin^2\theta_0, \text{ or } \Psi_1 = \theta_0 \quad \ldots\ldots (13)$$

The above discussion shows that when a minimum value of R between zero and unity exists, the orthogonal possesses complete symmetry with respect to the radius vector $\theta = \theta_m$.

Determination of orthogonals

The preceding discussion shows it is possible to obtain the orthogonals for specific cases when the function $C = C(R)$ is known. The circular bottom-contours associated with any particular function of this type are determined by the relationship [H. O., 1944, p. 5] of (14).

$$C/C_0 = \tanh\left[2\pi(d/L_0)(C_0/C)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

where d is the depth and L_0 is the deep-water wave-length. Eliminating C between the relationship $C = C(R)$ and (14) gives $R = f(d/L_0)$. Figure 2 shows cross-sections of the bottom for the cases which are now discussed. When $R = 1$, $C = C_0$ and in all cases d/L_0 is assumed equal to 0.5 at $R = 1$. This implies that the wave-velocity does not differ significantly from C_0 at values of d/L_0 greater than 0.5.

The inset of Figure 6 shows what is meant by the terms "lee of an island" and "lee shore of an island" which are used in the following discussion.

Case 1A: Point island

Assume $C/C_0 = R$, where $0 \leq R \leq 1$. Since (10) has no solution for R in this case other than $R = 0$, there is no minimum value R_m, and the solution of (9) with negative sign gives the orthogonal after the initial conditions are imposed.

$$R = 1/e^{(\theta - \theta_0)\operatorname{ctn}\theta_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Equation (15) is the equation of a logarithmic spiral. All orthogonals converge towards the center, $R = 0$, since R decreases as θ increases. Orthogonals corresponding to certain values of θ_0 are shown in Figure 3. Only orthogonals entering the quadrant $0 \leq \theta_0 < (\pi/2)$ are shown. A corresponding set of orthogonals entering the quadrant $(3\pi/2) < \theta_0 \leq 2\pi$ can also be drawn, and this is true also of the other cases discussed.

The cross-section of the bottom in Figure 2 shows that this case is the limiting case between an island and a shoal.

This case will be referred to as a "point island" and is significant because of the extreme convergence at the center. Any wave-crest which crosses the contour $d = 0.5\,L_0$ continually converges towards the center. As a result there are no refracted waves at all in the lee of the point island beyond the contour $d = 0.5\,L_0$.

Case 1B: Circular island

Assume $C/C_0 = (R - n)/(1 - n)$, where $0 < n < 1$ and $n \leq R \leq 1$. Since (10) has no root R between 0 and 1, there is no minimum value R_m. The solution of (9) with negative sign determines the orthogonal. In this case all orthogonals meet the shore of the island ($R = n$). Determine only the value of θ, θ_n, for $R = n$. Then, for $\theta_0 < \sin^{-1}(1 - n)$

$$\theta_n = \left[-1/\sqrt{(1-n)^2\csc^2\theta_0 - 1}\right]\log_e \frac{n\left[(\csc\theta_0)\sqrt{(1-n)^2\csc^2\theta_0 - 1} + (1-n)\csc^2\theta_0\right]}{(\operatorname{ctn}\theta_0)\sqrt{(1-n)^2\csc^2\theta_0 - 1} + (1-n)\csc^2\theta_0 - 1} \quad \ldots (16a)$$

For $\theta_0 > \sin^{-1}(1 - n)$

$$\theta_n = \left[1/\sqrt{1 - (1-n)^2\csc^2\theta_0}\right]\sin^{-1}\left[(1-n)\csc\theta_0\right] - \sin^{-1}\left\{\left[(1-n)\csc^2\theta_0 - 1\right]/n\csc\theta_0\right\} \quad (16b)$$

Equation (8) shows that $(dR/d\theta)$ becomes infinite as R approaches n, since in this case C approaches θ. This means that at the point $R = n$, $\theta = \theta_n$ the orthogonals are normal to the shore. This fact, together with the values θ_0, θ_n, and the initial direction, makes it possible to obtain an approximation of the orthogonal between $R = 1$ and $R = n$ without determining points in that range.

In considering wave-height, it is desirable to introduce K, the refraction-coefficient [H.O., 1944, pp. 18-21]. K is the factor by which deep-water wave-height must be multiplied to obtain the shallow-water wave-height resulting from the refraction effect alone.

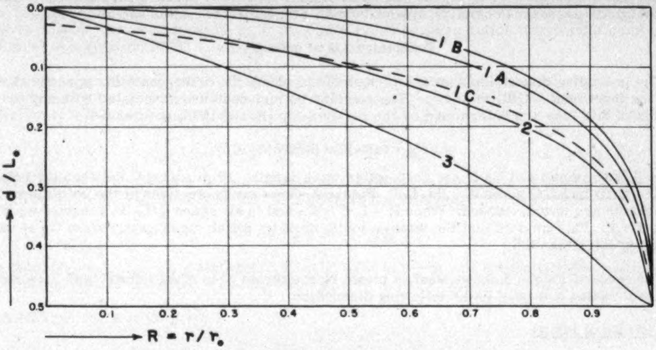

Fig. 2--Cross-sections of bottom-slopes for 5 cases

The orthogonals for certain values of θ_0 for n = 0.2 are shown in Figure 4. Values of θ_n corresponding to 15 values of θ_0 between 0° and 90° have been determined. The resulting values of K, at the shore, where d = 0, have been computed. Figure 4 shows a curve giving K at the shore for various values of θ_n.

Actually, the waves would break just off shore, but the value of K at the point of breaking would differ only slightly from the values given here.

The cross-section in Figure 2 shows that this case is that of an island whose radius is one-fifth of the distance from the center to the contour d = 0.5 L_0. As in Case 1A, the zone in the lee of the island beyond the contour d = 0.5 L_0 is completely free from refracted waves. The curve for K at the shore shows that for $0 \leq \theta_n \leq \pi$ the minimum value of K is 0.6. Interference between wave-trains refracted from each side of the island would produce waves higher than the incident waves all along the shore. Such an island has no lee shore as far as protection from incident waves is concerned.

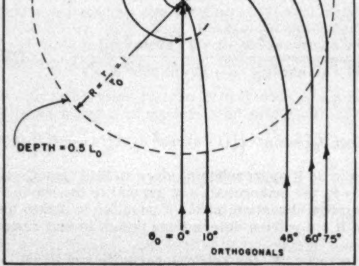

Fig. 3--Orthogonals for a "point island" off which the slope changes from very gentle to very steep, Case 1A

Case 1C: Shoal

Assume $C/C_0 = (1 - n)R + n$, where $0<n<1$ and $0 \leq R \leq 1$. Equation (10) has a root R between 0 and 1, and this root is the minimum value of R for the orthogonal.

$$R_m = n/[\csc \theta_0 - (1 - n)] \quad \ldots\ldots\ldots\ldots (17)$$

The value of θ_m can be obtained by use of equation (11) as in (18).

$$\theta_m = (\pi/2) + [(1 - n)/\sqrt{\csc^2 \theta_0 - (1 - n)^2} \log_e \left\{ (\operatorname{ctn} \theta_0)\sqrt{\csc^2 \theta_0 - (1 - n)^2} + [\csc^2 \theta_0 - (1 - n)^2] - n(1 - n)\right\} / n \csc \theta_0] \quad \ldots (18)$$

After θ_m is determined, θ_1 may be determined by (12)

Orthogonals for certain values of θ_0 with n = 0.4 are shown in Figure 5.

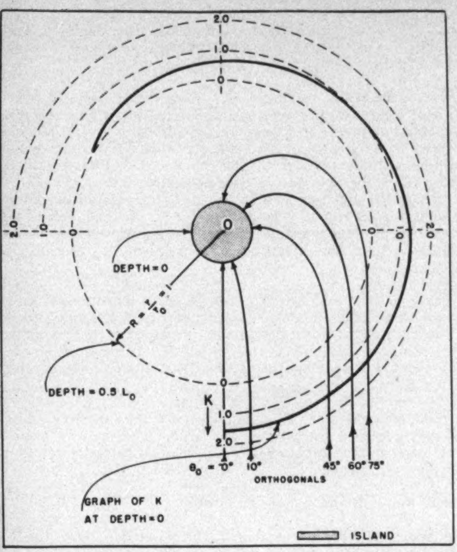
2.0
1.0
0
0
1.0
2.0
O
DEPTH = 0
R = 1/L0 = 1
DEPTH = 0.5 L0
K
1.0
2.0
θ0 = 0°
10°
45°
60°
75°
ORTHOGONALS
GRAPH OF K
AT DEPTH = 0
ISLAND

Fig. 4--Orthogonals and K-variation at shore for a circular island off which the slope changes from very gentle to very steep, Case 1B

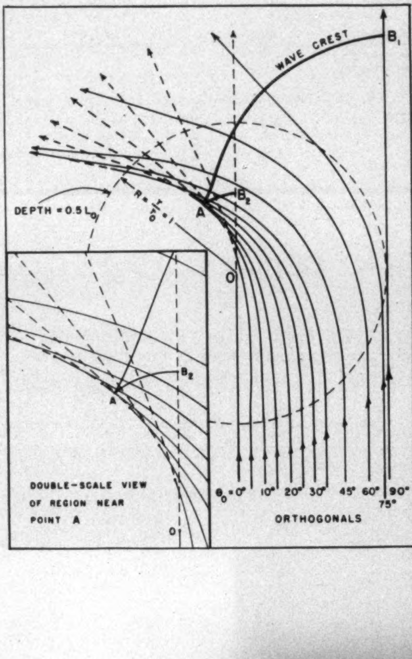
WAVE CREST
B1
B2
A
DEPTH = 0.5 L0
R = 1/L0 = 1
O
θ0 = 0°
10°
20°
30°
45°
60°
90°
75°
ORTHOGONALS
B2
A
DOUBLE-SCALE VIEW
OF REGION NEAR
POINT A
O

Fig. 5--Intersecting orthogonals associated with wave-crests passing over a shoal, Case 1C

The following three points have been determined for each orthogonal: $(1, \theta_0)$, (R_m, θ_m) and $(1, \theta_1)$. Since the direction at each point is known, the orthogonals shown are reasonably accurate. The cross-section in Figure 2 shows that this case is that of a shoal. At the most shallow point of the shoal $C = 0.4\ C_0$, and the depth at this point is $0.028\ L_0$.

There has been considerable discussion about the possibility of orthogonals associated with an undivided wave-train intersecting, and this case clearly shows that orthogonals can intersect. Beyond the center of the shoal, two crests exist as shown in Figure 5. Crest AB_1 is associated with the solid portion of the orthogonals, and crest AB_2 is associated with the dashed portion. Point A is located on what is known as the envelope of the orthogonals. The envelope is not drawn, but it may be visualized as a curve tangent to each of the orthogonals corresponding to values of θ_0 from zero up to a certain value. The orthogonal is drawn as a solid line to the point of tangency with the envelope. Thereafter the orthogonal is drawn as a dashed line. At a point of intersection between two orthogonals, each of the orthogonals is associated with a different wave-crest. Consequently at such an intersection point there is not what might be called a complete "focusing" effect and K is therefore not infinite.

K is also never infinite along the envelope, since no two orthogonals intersect at a point on the envelope. However, Figure 5 shows that a region of convergence exists along the envelope. The maximum value of K along any wave-crest occurs at a point on the envelope such as point A. Computation of the value of K at point O gives the approximate magnitude of the convergence occurring along the envelope. From (10) it can be shown that the value of K at point O is approximately 1.6.

Consideration of waves refracted from both sides of the shoal shows that the interference between the four crests would produce a very confused sea between the two envelopes. Waves are known to break in relatively deep water over shoals, and such breaking may be partially due to the combined effect of the convergence and interference.

Determination of K at a distance from an island

In Cases 1A and 1B all orthogonals approach the depth-contour $d = 0$. When the slope of the bottom is more nearly linear, most of the orthogonals do not reach the depth contour $d = 0$. In order to determine wave-heights in the lee of such islands it is desirable to study the variation of K along a circle of radius pr_0, $(p>1)$, with the center at the center of the circular or point island. An expression for K as determined by two orthogonals which are relatively close together is now developed.

Refer to Figure 6, and assume that the orthogonals are straight lines when $d>0.5L_0$, $(R>1)$. The angles Θ_1 and Θ_3 are then given by

$$\cos[\Theta_1 - (\theta_0 + \theta_1) + \pi/2] = (\sin\theta_0)/p \text{ and } \cos[\Theta_3 - (\theta_2 + \theta_3) + \pi/2] = (\sin\theta_2)/p \quad \text{. . . . .(19)}$$

Since $K = \sqrt{d\ell_0/d\ell}$, the value of K at the point $R = p$, $\theta = (\Theta_1 + \Theta_3)/2$ to a satisfactory degree of approximation is

$$K = \sqrt{(\sin\theta_2 - \sin\theta_0)/(\Theta_1 - \Theta_3)p} \quad \text{. . . . . (20)}$$

The values of K along a circle of radius $5r_0$ will be determined for two cases of point islands.

Case 2

Assume $C/C_0 = \sqrt{R}$, where $0 \leq R \leq 1$. Equation (10) has a root R between 0 and 1, and this root gives as the minimum value of R for the orthogonal

$$R_m = \sin^2\theta_0 \quad \text{. . . . . (21)}$$

The solution of (9) with negative sign gives the equation of the orthogonal

$$R = 2(\sin^2\theta_0)/[1 - \cos(\theta + \theta_0)] \quad \text{. . . . . (22)}$$

When $R = R_m$, the above equation gives $\theta_m = (\pi - \theta_0)$, and use of (12) gives $\theta_1 = (2\pi - 3\theta_0)$.

Equation (22) is the equation of a parabola with vertex at point (R_m, θ_m) and with the axis of symmetry the radius vector $\theta = \theta_m$. The cross-section of the bottom in Figure 2 shows a moderate bottom-slope in this case changing to a sharp slope near the contour $d = 0.5\,L_0$. Figure 7 shows orthogonals corresponding to certain values of θ_0 and a curve showing the variation in K along a circle of radius $5\,r_0$. Equation (20) was used to determine K at 28 points.

The curve for K indicates that the height of refracted waves is greatest for that portion of the wave-crest turned through the largest angle. As θ_0 approaches 0°, the angle through which the crest is turned approaches 180°. In the lee of the island wave-height increases rapidly with increasing θ.

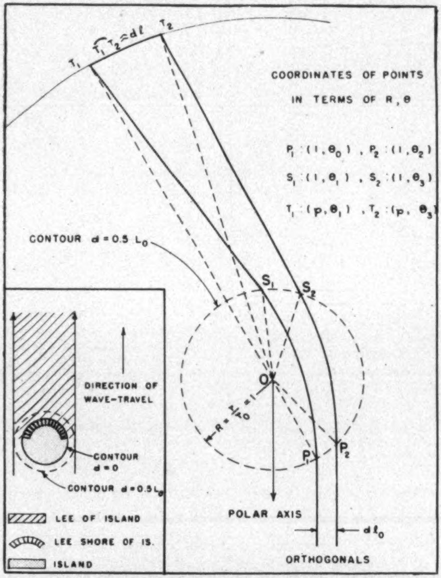
T_1
$\overset{\frown}{T_1 T_2} = dl$
T_2
COORDINATES OF POINTS
IN TERMS OF R, θ
$P_1 : (1, \theta_0)$, $P_2 : (1, \theta_2)$
$S_1 : (1, \theta_1)$, $S_2 : (1, \theta_3)$
$T_1 : (p, \theta_1)$, $T_2 : (p, \theta_3)$
CONTOUR $d = 0.5\,L_0$
S_1
S_2
O
$R = r/r_0 = 1$
P_1
P_2
POLAR AXIS
dl_0
ORTHOGONALS
DIRECTION OF WAVE-TRAVEL
CONTOUR $d = 0$
CONTOUR $d = 0.5\,L_0$
▨ LEE OF ISLAND
LEE SHORE OF IS.
ISLAND

Fig. 6--Diagram for determination of K at a distance from an island (inset illustrates meaning of term "lee")

Case 3:

Assume $C/C_0 = \sqrt{R(2-R)}$, where $0 \leq R \leq 1$. From (10)

$$R_m = 2\,(\sin^2\theta_0)/(1 + \sin^2\theta_0) \qquad (23)$$

By (11)

$$\theta_m = \pi - \theta_0 + [\sin^{-1}(\sin^2\theta_0) - \pi/2]/\sqrt{\csc^2\theta_0 + 1} \qquad (24)$$

The value of θ is given in terms of θ_0 and θ_m by (12).

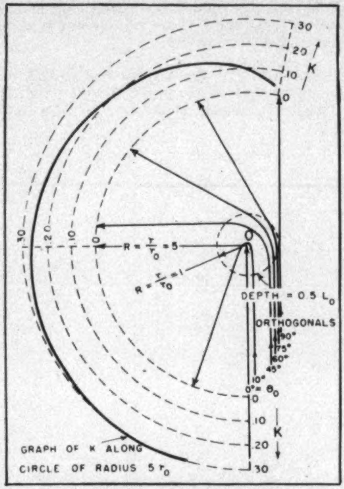
.30
.20
.10
0
K
.30
.20
.10
0
O
R = r/r0 = 5
R = r/r0 = 1
DEPTH = 0.5 L0
ORTHOGONALS
90°
75°
60°
45°
10°
0° = θ0
0
.10
.20
.30
K
GRAPH OF K ALONG
CIRCLE OF RADIUS 5 r0

Fig. 7--Orthogonals and K-variation (at distance R = 5) for a "point island" off which slope changes from moderate to steep, Case 2

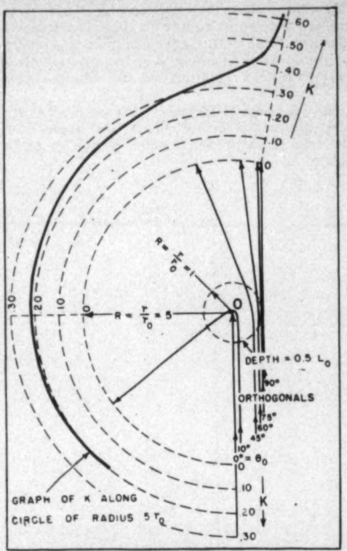
.60
.50
.40
.30
.20
.10
0
K
.30
.20
.10
0
O
R = r/r0 = 1
R = r/r0 = 5
DEPTH = 0.5 L0
90°
ORTHOGONALS
75°
60°
45°
10°
0° = θ0
0
.10
.20
.30
K
GRAPH OF K ALONG
CIRCLE OF RADIUS 5 r0

Fig. 8--Orthogonals and K-variation (at distance R = 5) for a "point island" off which the slope is approximately linear, Case 3

For this case, as shown in Figure 2, the slope of the bottom is almost linear. Orthogonals corresponding to certain values of θ_0 and a curve depicting the variation in K around a circle of radius $5r_0$ are shown in Figure 8. The curve is based on the determination of K at 15 points.

The curve for K shows a decrease in height of refracted waves for increasing θ. This decrease in wave-height is rapid in the lee of the island.

Summary and conclusions

The variation in refraction at a large distance from an island can be indicated by summarizing the effects associated with three different types of bottom slope:

Type 1, bottom-slope--Very steep slope near contour $d = 0.5\ L_0$ and very gentle slope in more shallow water (Cases 1A and 1B)
Refraction effect: No refracted waves in lee of island beyond contour $d = 0.5\ L_0$.

Type 2, bottom-slope--Steep slope near contour $d = 0.5\ L_0$ and moderate slope in more shallow water (Case 2)
Refraction effect: At a large distance refracted wave-height is very low at edge of lee but increases toward center of lee. Waves refracted through greater angles are higher.

Type 3, bottom-slope--Approximately linear bottom-slope (Case 3)
Refraction effect: At a large distance refracted wave-height rapidly decreases from incident wave-height at edge of lee to lower values towards center of lee. Waves refracted through greater angles are lower.

Islands where the bottom slope resembles Type 1 have waves on the lee shore as high as the incident waves if the radius of the contour $d = 0.5 L_0$ is large compared to the island radius. This type of bottom slope is characteristic of coral islands and volcanic islands with a shelf cut by wave-erosion. It is probable that a refraction effect of this type rather than diffraction explains the high breakers known to be frequent on the lee shore of certain islands.

Shoals with a steep slope near the contour $d = 0.5 L_0$ are characterized by intersecting orthogonals which indicate that a single incident wave-crest is divided into two crests. Shoals of this type exist in regions where glacial erosion has occurred. The associated convergence and interference may explain the confused sea and breaking waves frequently observed over such shoals.

The foregoing results indicate a need for especially great accuracy in the construction of refraction diagrams when the slope of the bottom is steep. The use of a large-scale chart and a small wave-interval is essential.

Acknowledgments

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TEMPERATURE MEASUREMENTS AT PARÍCUTIN VOLCANO[a]

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Abstract--(a) Evidence is presented which shows that the gases emitted by the Aguan flow of lava at Parícutin did not burn when they came in contact with the air. (b) The temperature of the lava at its source was estimated to be 1200° C and thus lies in the same range as that for other basaltic lavas. (c) Temperature-measurements were also made of the fumaroles located on the older Zapichu flow where a maximum of 640° C was recorded.

Parícutin Volcano came into existence in February, 1943, and has been almost continuously active up to the present writing [see 1 of "References" at end of paper, 1944 and 1945]. Explosive activity from the cone has been very common, but the quiet effusion of many lava flows from the flank of the cone has been in many respects the most impressive form of the activity. The lava is characterized by MILTON [1944] as basaltic in habit but andesitic in type. The total volume of lava that has issued since 1943 is large, but its magnitude is as yet not known. Studies are now under way by other investigators which should yield information on this point.

In December of 1944, at the invitation of the National Research Council, the writer was afforded the opportunity of making temperature-measurements of the Aguan lava which began to flow about November 10, 1944, and issued from the base of the cone on its southerly flank. In addition, measurements were made of the emanations issuing from a series of fumaroles located on the Zapichu flow which issued from the southern base of the cone some time during 1943.

Temperature-measurements at the Aguan flow--Several observers at Parícutin have noted the presence of excrescences, termed hornitos, near the edges of the hot lava flows. These are frequently cupola-shaped and, if not too active, are convenient orifices from which samples of gas can be taken and measurements of the temperature of the escaping gases can be made. Another type is nothing more than a large blob of congealed lava, perforated by channels. Unfortunately, none of the former type was active in December, 1944; but one of the latter was quite active, as shown by the fact that hot gases were freely emitted from all channels. It was about 1.25 meters high, one meter in diameter at the base, and was located close to the well from which the Aguan lava was issuing. Here one had a favorable opportunity for determining whether the gases emitted by the lava would burn when they came in contact with the air. Several of the channels, both near the top and at the bottom of the excrescence, were probed with a 22-gauge chromel-alumel thermocouple connected to a portable potentiometer. One of the leads was insulated with unglazed porcelain tubing, especially adapted for the purpose, for a distance of about one meter from the junction which was made by tightly twisting together the ends of the wire brightened by sandpapering. After every measurement, the junction was cut off and renewed. The element was inserted in a silica-glass jacket about 1.5 meters long in such a manner that the junction touched bottom. The leads were about ten meters long and were connected directly to the portable potentiometer. The cold junction was protected from extraneous sources of heat, its temperature was repeatedly taken, and the millivolt readings corrected accordingly. The entire assembly as used had been calibrated at the Geophysical Laboratory and was recalibrated on the return of the writer to Washington.

Working near an actively moving lava flow and in close proximity to the hot lava fragments ejected by the eruptions is fraught with considerable danger. The length of the leads specified above is required for the protection of the potentiometer and the observer. The entire apparatus must be so flexible that it can be quickly moved out of danger.[b]

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[a] This work was carried out as part of the cooperative study of Parícutin now being undertaken under the auspices of the Parícutin Committee of the National Research Council and of a parallel Committee of Mexican scientists.

[b] The writer is greatly indebted to HOWEL WILLIAMS, who recorded the results, WM. F. FOSHAG, who probed the hot areas, JENARO GONZALEZ and CELEDONIO GUITIÉRREZ for assistance in carrying out all the temperature measurements referred to in this presentation. In addition to performing the duties referred to, all assisted in keeping the leads off the ground, and in watching the vagaries of the erupting cone. They thus enabled the writer to confine his attention to the operation of the potentiometer with reasonable assurance of safety.

When the channels of the blob of lava were probed, it was found that the walls were so hot that a viscous plastic lava was encountered. The writer is indebted to Dr. FOSHAG for his skill in avoiding the loss of the valuable silica-glass jackets by preventing them from sticking to the walls.

Seventeen measurements were made at the hornito. No matter in what channels they were made, much higher temperatures were found at the bottom than at a distance of two to four inches from the orifice. The temperature at the latter position was about 890° C, whereas 60 cm down the maximum temperature was 1080° C. It seems safe to conclude that the gases from the Aguan flow did not burn when they came in contact with the air. Then, too, no flames were observed on the glowing and actively moving lava when seen at night time. Short blue flames were seen where the lava came in contact with dead trees; here, of course, combustible gases were developed by destructive distillation of the wood. Short yellowish flames containing brightly glowing particles were rarely seen where gases were vigorously ejected, but this is no proof for the existence of combustible gases. Any gas issuing at a temperature around 1100° C and carrying finely divided particles will exhibit such behavior.

Temperature of the lava--The Aguan flow of December 1944 chilled rapidly at the surface even close to its source, but it moved freely enough to develop fractures which revealed the glowing lava. Near the source, the emission of gas raised mounds of glowing lava whose straw color and brightness enabled the writer to make estimates of its temperature which, based on experience in viewing hot objects in the laboratory, proved to be between 1050° and 1250° C. RICHARD FULLER (private communication) in May, 1945, used an optical pyrometer in an effort to measure the temperature of similar blobs of straw-colored lava and estimated it to be between 1200° and 1250° C. The use of this type of pyrometer is fraught with difficulties, but the writer believes that the value obtained by FULLER is correct.

The lava observed by the writer at the source of the Aguan flow was flowing freely and was building up its own levees at the side of the stream. Fruitless efforts were made to measure its temperature with the thermocouple. It quickly became obvious that the thermocouple could stand more heat than the observers' bodies, and furthermore the hot levees provided a most insecure footing. A measurement was obtained in a relatively deep (30 cm) crack in the levee. The lava was viscous and had a temperature of 1020° C.

The next day an area was found, about three miles north from the source of the lava, where an actively moving flow broke out of the side of one of the lobes of the main flow. The lava here was somewhat more sluggish than near the source and instead of building up levees it flowed as a mass elevated about four feet above the ground. It was, however, moving actively enough so that freely-flowing lava was constantly exposed. Large blocks of surface-chilled lava would form and then split open in a manner that reminded one of pulling taffy. The glowing lava revealed by this taffy-pulling motion had a bright orange, almost yellow color; it was so plastic that a Marquardt unglazed porcelain tube containing a thermoelement could be inserted to a depth of about ten cm. These porcelain thermoelement jackets were about 30 cm long and were securely lashed to a wooden pole. This arrangement permitted one to push the jacket gently into the lava as far as its viscosity would allow. Maximum temperature was reached in about five minutes. The thermoelement was then withdrawn and the junction renewed. It was impossible to withdraw the porcelain jacket and hence it was necessary to use a new one for each temperature-measurement. The highest temperature recorded was 1110° C. Five measurements were made and all were close to the value just given. It should be borne in mind that this value was obtained at a position about three miles from the source and that the lava had taken about a month to flow this far. The thermal insulation provided by the chilled protecting surface of the flow evidently must be very good indeed.

It can be readily understood that the task of making these measurements was not particularly pleasant, but it was well worth the trouble.

The taffy-pulling motion together with the recorded temperature of about 1100° C indicated that a rise in temperature of about 100° to 150° C would produce a freely-flowing lava such as seen at the source. The evidence obtained with the optical pyrometer and with the thermocouple points to a value of 1200° C as being a close approximation to the temperature of the lava as it issues from the base of the volcano. It is of interest to note that this value for the basaltic lava of Parícutin lies in the same range as that obtained by DAY and SHEPHERD [1913] and JAGGAR [1917] for the temperature (1185° - 1200° C) of the basaltic lava of Kilauea and by VERHOOGEN [1939] for the temperature (1160° C) of the freely-flowing basaltic lava of Nyamlagira in Africa.

Temperatures of fumaroles--When fresh lava issues from a volcano, it emits gaseous products from its surface and continues to do so until all obvious motion of the flow has ceased. By this time the temperature at and near the surface is usually that of the air. If the flow has a thickness of ten or more meters and is not broken up by intense fracturing, then the interior can remain very hot for many months, and if paths of egress are present gaseous emanations will be emitted. Such fumarolic activity will continue until the temperature of the interior of the flow has fallen to about 500° C.

The northeast branch of the Zapichu flow of October, 1943, at a distance of about 1.5 miles from the source, exhibited fumarolic activity for a period of at least a year. In December of 1944, temperature-measurements were made of the emanations in order to correlate them, if possible, with the products given off by the lava and the products formed by the chemical interaction of the emanations and the lava over which they were passing.

All of the fumaroles investigated were located on a mound of the northeast branch of the Zapichu flow. The openings were probed with the chromel-alumel thermocouple inserted in a silica-glass jacket in much the same manner as indicated above. Care has to be exercised that the leads to the potentiometer are kept off the ground, which in the vicinity of the fumaroles is usually covered with moist reaction products that can short circuit the thermoelement junction and give erroneous readings on the potentiometer. The top of the mound was made up of material cemented together by chemical reaction products and only rarely were openings found that could be probed to a greater depth than about eight cm. The moist ground indicated that steam was present in the emanations, but with the exception of one opening at the side of the mound no conspicuous cloud of steam was noted at any of the fumaroles. The fumes escaped quietly as a thin, blue, evidently hot haze. The one opening from which visible steam issued could be probed to a depth of one meter, where a temperature of 105° C was obtained. All of the "blue" fumaroles exhibited much higher temperatures, varying from 350° to 640° C. The latter value was obtained at an opening located at the top of the mound. In view of the fact that the orifices of these "blue" fumaroles could be probed to a depth of only about eight cm, it seems plain that the source within the interior of the mound must be considerably hotter. These fumaroles persisted for more than a year after the emission of the flow, and their high temperature close to the surface is again evidence of the effectiveness of the thermal insulation afforded by the exterior mantle of lava. This lava was not obviously fractured but instead had been compacted by the cementing action of the products formed by the interaction of the emanations, emitted at elevated temperatures, and the lava. These products, called incrustations, were collected by Dr. FOSHAG after the temperature-measurements were made and it is hoped that they will be subjected to geochemical investigation.

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THE EFFECT OF ORGANIC MATTER, GYPSUM, AND DRYING ON THE INFILTRATION RATE AND PERMEABILITY OF A SOIL IRRIGATED WITH A HIGH SODIUM WATER

R. F. Reitemeier and J. E. Christiansen

(Contribution from the U. S. Regional Salinity Laboratory, Riverside, California, Bureau of Plant Industry, Soils, and Agricultural Engineering, Agricultural Research Administration, U. S. Department of Agriculture, in cooperation with the eleven western states and the Territory of Hawaii.)

Abstract--Experiments designed to determine the effects of gypsum and organic matter on the infiltration rate of relatively impermeable soils were conducted in the Coachella Valley of southern California on an area devoted to the growing of date palms. The irrigation water used was relatively low in salts, a high percentage of which was in the sodium cation. It was found that spading gypsum into the soil at a rate of five tons per acre, or organic matter in the form of chopped alfalfa at the same rate, were both highly effective in that they both approximately doubled the infiltration rate during a two-year experiment. It was found that a prolonged drying period, between times of infiltration, extending to the wilting range, was even more effective in increasing the rate of infiltration. Laboratory experiments on permeability generally supported the field results.

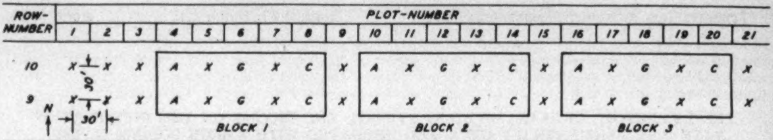
Although coarse in texture, some soils in the Coachella Valley of southern California are relatively impermeable, and adequate penetration of irrigation water is difficult to obtain. The waters used in this area often have a low total salt content with a high ratio of sodium to the other cations. The experiment reported here was designed to investigate the response of the soil and date palms to gypsum and organic matter, with special reference to rate of infiltration, depth of water penetration, leaf elongation, and laboratory measurements of permeability and related soil properties. The beneficial effects of gypsum and organic matter on some soils have long been recognized. A recent investigation in which their value was demonstrated is that of HUBERTY and PILLSBURY [see "References" at end of paper, 1941]. This paper reports results of measurements of infiltration and permeability.

Location of experimental area--The experiment was conducted in a 15-year old Deglet Noor date palm planting at the Torrez-Martinez Indian Reservation, about ten miles southeast of Indio, California.

Nature of soils--The soil is classified as Indio very fine sandy loam. It is of recent water- and wind-borne origin and is irregularly stratified, with no uniformity in thickness, texture, or order of strata. The cultivated topsoil is fairly homogeneous, probably owing to repeated mixing. Sands predominate at lower depths, although strata of clay and silt occur at irregular intervals. The soil is micaceous, low in organic matter, gray in color, rich in soluble minerals, and contains calcium carbonate and small shells throughout the four-foot profile. It has a relatively high water-holding capacity for a soil of its texture. Consequently, heavy applications of water are required to obtain adequate penetration. PILLSBURY [1941] has attributed this "high effective field capacity" of coarse Coachella Valley soils to the complex stratification.

Character of water supply--The water supply for the valley, obtained from deep wells, generally contains only small quantities of salts. At the Reservation, the water has a total salt concentration of 2.44 epm (189 ppm) of which the sodium and bicarbonate percentages are 82 and 64, respectively. The low permeability of the soils at this location has been attributed to the high sodium percentage of the water, and it was believed that the inferior fruit from these palms might result from an inadequate moisture supply, or from the accumulation of sodium salts in the soil.

Experimental design--The planting consists of two rows of 21 palms extending from east to west with row 10 north of row 9. The palms are spaced 30 feet apart in each direction. The two basins around each pair of palms are considered a plot. Nine alternate plots were selected for three replications of three treatments: control, alfalfa, and gypsum. The plot design is shown in Figure 1. Plots 4, 6, and 8 comprise block 1; plots 10, 12, and 14, block 2; and plots 16, 18, and 20, block 3.



TREATMENT: A = ALFALFA, G = GYPSUM, C = CONTROL, X = BORDER

Fig. 1--Arrangement of experimental plots

All plots were disced and leveled during the last week of April, 1941. Individual palm basins, 30 × 30 feet, were enclosed by levees. Powdered gypsum and chopped alfalfa were applied on the plots indicated at the rate of five tons per acre, and spaded in by hand, and the control plots were spaded similarly. The same treatments were repeated prior to the June 6 irrigation, except that the alfalfa was more finely ground. On March 23, 1942, all plots were cultivated, and chopped alfalfa applied to plots 4, 10, and 16 at the rate of five tons per acre.

Eleven applications of water totaling 54 inches in depth were made from May 1 to September 12, 1941, and 13 applications totaling 78 inches between April 1 and September 1, 1942. To determine the effect of thorough drying on leaf elongation and fruit formation, the border plots were not irrigated between March 23 and June 1, 1942, while the experimental plots were irrigated four times. The irrigation water was delivered to each plot through a four-inch portable pipe line and measured with a totalizing water meter.

During 1941 it became evident that four-inch irrigation applications did not penetrate to a sufficient depth, and that the rate of infiltration improved on more thorough drying. The water applications were increased to six inches at the seventh 1941 irrigation, and beginning with the second 1942 irrigation, double six-inch applications were made, the second being made three to four days after the first. Irrigation dates, intervals between irrigations, and depths of water applied are listed in Table 1.

Table 1--Irrigation schedule, 1941 and 1942

1941				1942			
No.	Date	Interval	Depth of water	No.	Date	Interval	Depth of water
		days	in			days	in
1	May 1	--	4	--	Apr. 6	--	6
2	May 12	11	4	--	Apr. 20	14	6
3	May 22	10	4	--	May 6	16	6
4	June 6	15	4	--	May 19	13	6
5	June 17	11	4	1	June 3	15	6
6	June 26	9	4	2a	June 23	20	6
7	July 8	12	6	2b	June 26	3	6
8	July 29	21	6	3a	July 14	18	6
9	Aug. 14	16	6	3b	July 17	3	6
10	Aug. 28	14	6	4a	Aug. 3	17	6
11	Sept. 9	12	6	4b	Aug. 7	4	6
				5a	Aug. 24	17	6
				5b	Aug. 27	3	6

During irrigations, rates of infiltration in the nine treatment basins of row 10 were measured automatically by special water-stage recorders. During 1942 additional infiltration data were obtained in the basins of row 9, and the border basins of row 10, by reading the depth of water on graduated stakes. Soil moisture data were obtained by tensiometers [RICHARDS, 1942], with cups placed at one-foot intervals to a depth of four feet. Measurements of leaf elongation were made on the 18 experimental palms three times a week by the method of MOORE and ALDRICH [1939]. On September 24, 1941, and November 4, 1942, soil samples were removed from the nine treated plots for chemical and physical laboratory measurements. These measurements included permeability, dispersion ratio, flocculation, one-third atmosphere tension percentage [RICHARDS and WEAVER, 1944], soluble salts, exchangeable bases, pH values, and organic-matter content. Only the results of infiltration and permeability measurements are reported at this time.

Results

Because the rate of infiltration decreases during the absorption of the irrigation water, it is difficult to assign a single value to an irrigation for plot and treatment comparisons. Inspection of the results indicated the average rate at which the second inch of water entered the soil to be an acceptable index of the rate of infiltration. In Table 2 are shown the infiltration rates for the second inch for the 11 irrigations of 1941. These values were subjected to an analysis of variance [SNEDECOR, 1938], which demonstrated highly significant differences between treatments, blocks, and irrigations. The plot means and standard errors for the alfalfa, gypsum, and control treatments in inches per hour were 0.31 ± 0.033, 0.36 ± 0.022, 0.16 ± 0.012, respectively. No significant difference existed between the alfalfa and gypsym treatments, but both were highly significantly greater than the control. Block one possessed values highly significantly greater than those of blocks 2 and 3; the mean values were 0.36 ± 0.034, 0.22 ± 0.022, and 0.24 ± 0.021, respectively. Significant and highly significant differences between irrigations were positively correlated with the length of interval between irrigations. The high values for the fourth irrigation result from the treatments and cultivation immediately preceding it.

Table 2--Infiltration rates for second inch of water in 1941

Plot	Treatment	Irrigation number										
		1	2	3	4	5	6	7	8	9	10	11
		in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
4	A	0.41	0.23	0.21	0.78	0.50	0.46	0.54	0.62	0.58	0.54	0.58
6	G	0.50	0.35	0.32	0.49	0.40	0.38	0.55	0.60	0.50	0.48	0.53
8	C	0.18	0.11	0.12	0.17	0.11	0.10	0.13	0.19	0.12	0.10	0.13
10	A	0.27	0.12	0.12	0.50	0.37	0.27	0.29	0.31	0.22	0.23	0.55
12	G	0.22	0.17	0.15	0.19	0.21	0.20	0.27	0.44	0.26	0.29	0.28
14	C	0.17	0.10	0.10	0.18	0.11	0.09	0.15	0.20	0.11	0.12	0.10
16	A	0.14	0.11	0.10	0.17	0.13	0.13	0.19	0.21	0.15	0.15	0.14
18	G	0.50	0.26	0.23	0.40	0.30	0.25	0.46	0.55	0.39	0.38	0.33
20	C	0.31	0.13	0.12	0.34	0.18	0.15	0.27	0.34	0.14	0.16	0.13

Notes: A = Alfalfa; G = Gypsum; C = Control.

In Table 3 are listed the mean rates in 1941 for the first, second, and third inch, and the final rate for the nine treatment plots, accompanied by their standard errors. The rate for the first inch is twice that for the second inch, whereas the latter corresponds more closely to the succeeding rates.

Table 3--Mean rates of infiltration in 1941

Plot	Treatment	First inch	Second inch	Third inch	Final[a]
		in/hr	in/hr	in/hr	in/hr
4	A	1.10 ± 0.153	0.50 ± 0.05	0.39 ± 0.036	0.35 ± 0.011
6	G	0.84 ± 0.045	0.46 ± 0.027	0.36 ± 0.024	0.38 ± 0.047
8	C	0.28 ± 0.023	0.13 ± 0.009	0.10 ± 0.007	0.11 ± 0.009
10	A	0.75 ± 0.136	0.30 ± 0.041	0.20 ± 0.022	0.15 ± 0.007
12	G	0.53 ± 0.050	0.24 ± 0.024	0.16 ± 0.008	0.18 ± 0.018
14	C	0.32 ± 0.051	0.13 ± 0.012	0.09 ± 0.008	0.09 ± 0.010
16	A	0.38 ± 0.033	0.15 ± 0.010	0.12 ± 0.007	0.10 ± 0.004
18	G	0.71 ± 0.063	0.37 ± 0.032	0.27 ± 0.018	0.25 ± 0.023
20	C	0.47 ± 0.066	0.21 ± 0.027	0.15 ± 0.020	0.13 ± 0.021

Notes: A = Alfalfa; G = Gypsum; C = Control. [a] Means for last five irrigations only.

Table 4 contains the inch rates for the second inch for six irrigations of 1942. The rates for the two irrigations applied after an interval of three days, 2b and 3b, average only about one-half those of the irrigations applied after an average interval of 18 days. Analysis of variance and tests for significance of the values of irrigations 1, 2a, 3a, and 4a showed the same effect of treatments and blocks as the 1941 results. The means for the three treatments in inch per hour were 0.31 ± 0.035, 0.28 ± 0.028, and 0.15 ± 0.011, and for blocks 0.34 ± 0.036, 0.22 ± 0.24, and 0.18 ± 0.014. Similar analysis of the results of irrigations 2b and 3b provided identical conclusions, with treatment means of 0.18 ± 0.032, 0.16 ± 0.030, and 0.10 ± 0.011, and block means of 0.22 ± 0.29, 0.12 ± 0.012, and 0.10 ± 0.008 inch per hour.

Table 4--Infiltration rates for second inch of water in 1942

Plot	Treat-ment	Irrigation number					
		1	2a	(2b)	3a	(3b)	4a
		in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
4	A	0.38	0.46	(0.26)	0.48	(0.29)	0.48
6	G	0.39	0.46	(0.25)	0.36	(0.25)	0.34
8	C	0.15	0.22	(0.14)	0.17	(0.12)	0.18
10	A	0.17	0.21	(0.14)	0.34	(0.14)	0.34
12	G	0.24	0.30	(0.15)	0.23	(0.12)	0.23
14	C	0.12	0.17	(0.09)	0.12	(0.08)	0.11
16	A	0.17	0.24	(0.11)	0.22	(0.12)	0.20
18	G	0.15	0.24	(0.09)	0.18	(0.10)	0.20
20	C	0.09	0.15	(0.07)	0.13	(0.08)	0.13

Notes: A = Alfalfa; G = Gypsum; C = Control. The rates for the "b" irrigation, or second half of the 12-inch application, are enclosed in parentheses.

Mean rates of infiltration for the first, second, third, and fifth inch of irrigations 1, 2a, 3a, and 4a of 1942 are listed in Table 5. These data confirm the 1941 results.

Table 5--Mean infiltration rates in 1942 during irrigation numbers 1, 2a, 3a, 4a

Plot	Treat-ment	First inch	Second inch	Third inch	Fifth inch
		in/hr	in/hr	in/hr	in/hr
4	A	1.00 ± 0.056	0.45 ± 0.024	0.34 ± 0.024	0.27 ± 0.018
6	G	0.76 ± 0.053	0.39 ± 0.026	0.30 ± 0.024	0.21 ± 0.013
8	C	0.37 ± 0.030	0.18 ± 0.015	0.13 ± 0.013	0.11 ± 0.009
10	A	0.56 ± 0.108[a]	0.26 ± 0.044	0.15 ± 0.026[a]	0.14 ± 0.022[a]
12	G	0.51 ± 0.027	0.25 ± 0.017	0.17 ± 0.016	0.15 ± 0.006
14	C	0.32 ± 0.029	0.13 ± 0.013	0.10 ± 0.009	0.08 ± 0.008
16	A	0.61 ± 0.033	0.21 ± 0.015	0.13 ± 0.012	0.12 ± 0.010
18	G	0.42 ± 0.029	0.19 ± 0.019	0.13 ± 0.013	0.11 ± 0.015
20	C	0.28 ± 0.020	0.12 ± 0 013	0.08 ± 0.005	0.07 ± 0.004

Notes: A = Alfalfa; G = Gypsum; C = Control. [a] Rates for irrigation 4a missing.

Table 6 presents a comparison between the border plots and the other experimental plots for three 1942 irrigations. In irrigation number 1, the border plots, which had missed four irrigations between March 23 and June 1, showed rates two to 13 times as high as those of the treated and control plots. In irrigations 2b and 4a, this effect was still evident although somewhat diminished.

Table 6--1942 infiltration rates for second inch of water in border and treated plots

Plot	Treat-ment	Irrigation number			Plot no.	Treat-ment	Irrigation number		
		1	(2b)	4a			1	(2b)	4a
		in/hr	in/hr	in/hr			in/hr	in/hr	in/hr
3	B	1.00	(0.58)	0.67	13	B	0.83	(0.18)	0.31
4	A	0.38	(0.26)	0.48	14	C	0.12	(0.09)	0.11
5	B	1.54	(0.44)	--	15	B	0.59	(0.19)	0.13
6	G	0.39	(0.25)	0.34	16	A	0.17	(0.11)	0.20
7	B	0.61	(0.27)	--	17	B	0.56	(0.14)	0.38
8	C	0.15	(0.14)	0.18	18	G	0.15	(0.09)	0.20
9	B	--	(0.22)	0.32	19	B	1.14	(0.24)	0.43
10	A	0.17	(0.14)	0.34	20	C	0.09	(0.07)	0.13
11	B	--	(0.27)	--	21	B	0.65	(0.27)	0.42
12	G	0.24	(0.15)	0.23					

Notes: B = Border; A = Alfalfa; G = Gypsum; C = Control.

Thus, the beneficial results of the desiccation persisted even two months after the "dry" period of the border plots had ended.

The method of laboratory measurement of permeability employed was the technique described by FIREMAN [1944] using a synthetic water of approximately the same composition as that of the natural irrigation water. Permeabilities expressed in cm per hour were calculated from the following form of the DARCY equation [CHRISTIANSEN, 1944; RICHARDS, 1940]:

$$P = QL/AH$$

where P is the DARCY coefficient of permeability, Q is the flow (volume per unit time), L is the length of the soil column, A is the cross-sectional area of the column and H is the decrease in hydraulic head through length L. The permeability value reported is that existing when 300 ml of water (2.86 in) had passed through 200 gm of soil. This volume of percolate occurs in the first phase of a prolonged permeability test [CHRISTIANSEN, 1944]. On September 24-25, 1941, soil samples were removed from each of the nine treatment basins of row 10 at two sample sites: I, halfway between the palm trunk and the southwest corner of the basin, and II, halfway between the trunk and the northeast corner of the basin. Samples were taken at the following depths: 3-9, 15-21, 27-33, and 39-45 inches. In the spring of 1942, permeability measurements were made on the moist samples. In December, 1944, permeability was re-determined on sub-samples of the eighteen 3-9 inch samples which had been air-dried and passed through a 2-mm round-hole screen.

Values are not reported for the 15-21, 27-33, and 39-45 inch horizons, because the stratified character of the subsoil precludes adequate sampling. However, the results indicate that some of the 27-33 and 39-45 inch horizons possess the lowest permeabilities, and the 3-9 inch horizon the highest. This is contrary to the trend of particle size, which generally increases with depth, but may be explained by the accumulation of sodium in the lower horizons. Because of high sodium content, many percolates of the subsoil samples were opaque from suspended clay and silt. The permeability coefficients for the 3-9 inch samples are listed in Table 7.

Table 7--Permeability coefficients of 1941, 3 - 9 inch soil samples after percolation of 300 ml of water

Sample site	Permeability								
	Alfalfa plots			Gypsum plots			Control plots		
	4	10	16	6	12	18	8	14	20
	cm/hr	cm/hr	cm/hr	cm/hr	cm/hr	cm/hr	cm/hr	cm/hr	cm/hr
					Moist samples				
I	1.48	1.25	1.57	2.12	2.03	2.72	0.62	0.65	1.45
II	1.06	1.35	1.64	1.53	2.09	1.77	0.79	1.99	1.06
Av.	1.27	1.30	1.61	1.83	2.06	2.25	0.71	1.32	1.26
					Air-dry samples				
I	4.25	1.28	4.67	3.12	5.8	4.55	1.84	3.90	3.10
II	4.55	8.11	2.88	4.32	7.15	5.5	1.99	7.2	1.97
Av.	4.4	4.7	3.8	3.7	6.5	5.0	1.9	5.6	2.5

It must be emphasized that these laboratory results can be used only with relation to each other and that no absolute comparison with field results is intended. The results on the moist and the dry samples were subjected to separate analyses of variance with regard to the following sources of variation: treatments, blocks, and sample sites within plots.

In the moist condition, the permeability is highly significantly affected by treatment but not by plot or sample location. The mean coefficients in centimeters per hour for the alfalfa, gypsum, and control treatments are 1.39 ± 0.088, 2.04 ± 0.164, and 1.09 ± 0.220, respectively. The gypsum coefficient is significantly higher than the alfalfa coefficient and highly significantly greater than the control, but the alfalfa and control means do not differ significantly.

After drying, the samples showed no significant difference with respect to treatment, blocks, or sample sites. This indicates that drying as an additional treatment outweighs the effects of the alfalfa and gypsum treatments, which supports the infiltration results. Unfortunately, the results on the moist and the air-dried samples cannot be directly compared, because changes in permeability occur during storage in a moist condition, and because it has not been possible to handle soil samples so that any difference in results can be attributed entirely to moisture content.

Conclusions

(1) The addition of gypsum and chopped alfalfa to a relatively coarse soil irrigated with a water of low salt content but high percentage of sodium approximately doubled the rate of infiltration during a two-year experiment.

(2) Prolonged drying of the soil by date-palm roots to the wilting range of moisture increased the rate of infiltration even more than the gypsum and alfalfa treatments.

(3) Laboratory measurements of permeability generally supported the field results.

(4) A doubling of the rate of infiltration often may be of practical importance. Thus, an increase in rate from 0.1 to 0.2 inch per hour reduces the time of entry for a six inch irrigation from 2-1/2 to 1-1/4 days.

(5) The beneficial effect of drying suggests two economical solutions to infiltration problems involving soils, waters, and crops of this character, namely, (a) the application of relatively heavy irrigations at long intervals, and (b) the irrigation of alternate rows or middles at each irrigation to provide further opportunity for drying of the soil without injury to the palms.

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RETARDANCE COEFFICIENTS FOR LOW FLOW IN CHANNELS LINED WITH VEGETATION

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(Contribution from the Stillwater Hydraulic Laboratory, Research Project OK-R-3, in cooperation with the Oklahoma Agricultural Experiment Station)

Abstract--The results of studies of the flow of water through various grass and legume covers are presented. The paper is concerned with low flows which are defined as those coursing through a vegetal cover without completely inundating the plants. The retardance to flow is expressed in MANNING'S n. The relation of n with depth and velocity of flow, since these affect the position and behavior of the vegetation, is presented.

Introduction--The coefficient n in the widely used MANNING formula $V = 1.486\, R^{2/3} S^{1/2}/n$ will be evaluated for shallow flows for a number of grasses and legumes differing widely in physical characteristics. The values have practical application in soil and water conservation, in flood control, and in land drainage and irrigation.

Extensive studies of the flow of water through and over vegetation (primarily the latter) were carried on by the United States Soil Conservation Service in its outdoor hydraulic laboratory at Spartanburg, South Carolina, from 1937 to 1941. A complete presentation of data and results has been made [see REE and PALMER in "References" at end of paper, 1946]. The study of the stability of steep channels lined with vegetation and the retardance of flow by the vegetation was the main effort of that laboratory. From 1940 to 1943 the Agricultural Experiment Station of the Oklahoma Agricultural and Mechanical College conducted experiments with vegetation-lined channels at Stillwater, Oklahoma, with the same objective. Some of the results have been presented by COX [1942]. In 1941 the Soil Conservation Service began the development of the Stillwater Hydraulic Laboratory at Stillwater, Oklahoma. Experimental data from all three of these sources were utilized in developing this paper. Appreciation is expressed to the Oklahoma Agricultural Experiment Station for use of a portion of its data.

The flow of water in a thin layer over soil surfaces has been variously termed "sheet flow," "shallow flow," and "overland flow." The hydraulics of flow over a vegetated slope involve the relationship of depth and velocity of flow to the height and physical structure of the vegetation. Since none of the above terms applies satisfactorily, a new designation, "low flow," will be used here. A flow ceases to be classed as low when its depth and velocity are such that bending and complete inundation of vegetation occur. Thus, "low flow" varies in depth and velocity according to land slope and the physical structure of the vegetation.

All previously reported data on overland flow on vegetated slopes, except those reported by REE [1939], appear to be derived from either watershed rainfall-runoff studies, natural-rainfall plot studies at experiment stations, or simulated-rainfall plot experiments. An average surface detention for the entire watershed or plot is obtained in analyzing such data by methods pioneered by HORTON [1935]. In the material to be presented here, the depth is a measured value at which a specific discharge is flowing. As such it has direct application in determining coefficients representing resistance to flow.

The data are not sufficiently complete to attempt a thorough analysis of the nature of the flow, that is, whether laminar or turbulent or mixed flow. REYNOLDS number, a dimensionless parameter commonly used to indicate the character of flow, cannot be readily applied since flow is relatively uneven over a soil surface. The proper velocity and depth values to use are elusive. It is certain that mean velocity and figures of mean depth are too low since a large percentage of the flow is carried in small channels rather than in a thin uniform sheet over the surface of the soil. Even though the depth of flow would be quite uniform, the mean velocity as computed is too low since that area blocked out by the vegetation is not considered. For extremely divided flow, such as that through dense Bermuda grass, there is the question of what length dimension to use. Results from preliminary investigations of the data, such as shown in Figure 1, where the discharge varies as the 5/3 power or less of the depth, suggest that all flows may be considered turbulent. The scarcity in current literature of design information concerning shallow flows over vegetated slopes justifies the presentation of certain preliminary results at this time.

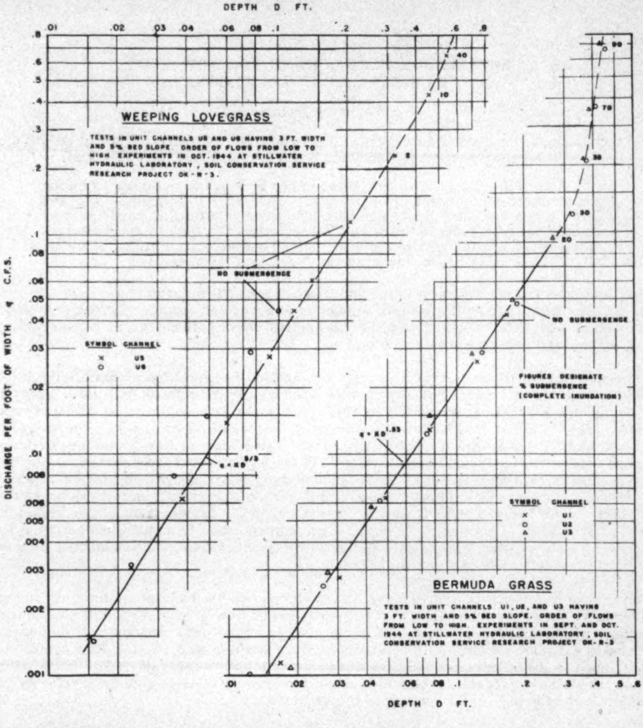

Fig. 1--Relationship of depth to discharge for weeping lovegrass and Bermuda grass

Description of experiments--The data presented were obtained from so-called "unit channels" such as those illustrated in Figure 2. These are flat-bottomed channels having very low permanent walls with higher smooth vertical walls in place only during the testing period.

Information relating to the experiment is presented in Table 1, and the results of the experiments in Table 2. Figures 3 and 4 show details of the channels and the condition of the Bermuda grass and weeping lovegrass tested at the Stillwater Hydraulic Laboratory.

The method of conducting an experiment was as follows: A flow of constant discharge was admitted at the head of each channel and when the outflow became constant, measurements of depth were made with point gages at a minimum of three stations at least ten feet apart. Bed measurements were made with the same equipment in a similar manner. Readings to 0.001 foot were taken at 0.2-foot intervals across the channel.

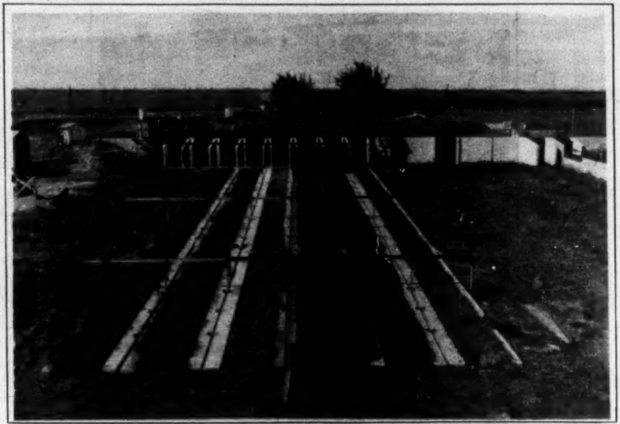

Fig. 2--Unit channels U1 to U6 (right to left) at the Stillwater Hydraulic Laboratory with covers of Bermuda grass and weeping lovegrass

For the shallowest flows used at the Stillwater Hydraulic Laboratory, the inflow discharges were reduced by the infiltration rates (assumed to be constant over the entire channel) to a value for each cross-section station. For the other channel experiments the channel outflow was not measured. This does not seriously affect the results, since the inflow rates of those experiments were relatively large in respect to possible infiltration losses. The soil loss was negligible for all low flows.

Retardance of flow--MANNING'S n, commonly called the roughness coefficient, will herein be termed "retardance coefficient" since it includes the effect of all factors tending to retard the flow and, in addition, the effects of the channel area blocked out by the vegetation. The depth, D, for shallow flows approximates the hydraulic radius, R. Thus, the forms of MANNING'S expression used here are $V = 1.486\, D^{2/3} S^{1/2} / n$ and $q = 1.486\, D^{5/3} S^{1/2} / n$ where V = velocity in ft per sec; D = depth in feet; S = slope in feet per foot; q = discharge per foot of width in cfs; and n = retardance coefficient.

Figure 5 is an illustration of the complete hydraulic behavior of vegetation as reflected in the retardance coefficient n. A division of the flows into three types based on hydraulic behavior is indicated. The data presented here lie within the low flow range in which the flow courses through a forest of stems and foliage without bending and completely submerging them. In the intermediate flow range the vegetation is in the process of bending over and becoming inundated. The retardance decreases very rapidly with depth. For high flows the vegetation tends to lie prone and the resisting element remains practically unchanging as depth increases.

The resistance to water flow offered by a specific vegetal cover depends upon (a) the presence or absence of a surface mulch, (b) the depth (because of physical changes of the vegetation), and (c) the position of the vegetation in the flow area. Item (a) depends upon the type and age of the cover, previous treatment, and whether or not portions of the plant debris, if any, have been moved about into minute dams or floated out by previous flows. The position of the vegetation of any given species in the flow is a function of the bending moment, which is determined by depth and velocity. The effect of these on water flow is expressed reasonably well in the retardance coefficient n. It should be borne in mind that this coefficient here represents not only the effect of bed roughness and boundary resistance offered by the vegetation but also that of reduction in cross-sectional area of channel and any other factor tending to retard the flow.

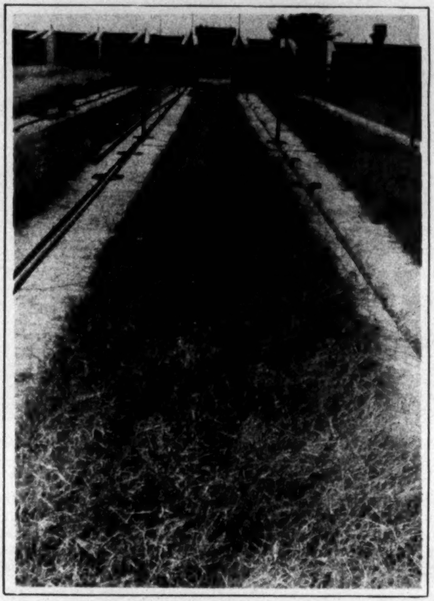

Fig. 3--Condition of Bermuda grass in unit channels U1, U2, and U3, at time of testing

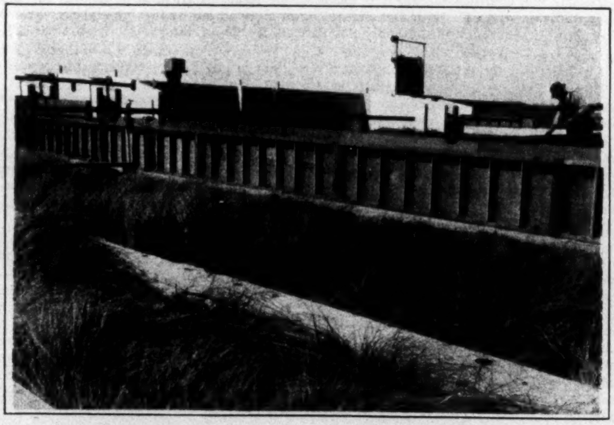

Fig. 4--Condition of weeping lovegrass in unit channels U5 and U6 at time of testing. Note plywood sidewalls in place to contain the deeper flows for channel U3

Table 1--Description of experiments

Vegetation	Vegetation measurements					
(All vegetation green at times of test)	Channel	Nominal bed slope	Date tested	Average length	Stand count	Forage cover
		per cent		in	stems per sq ft	cu in per sq ft
Bermuda--dense, uniform cover, established by sprigging in spring, 1944 [a]	U1	5	Oct.1944	5	480	-
	U2	5	Oct.1944	5	480	-
	U3	5	Oct.1944	5	480	-
Weeping lovegrass--good uniform stands, established from broadcast seed in spring, 1944 [a]	U5	5	Oct.1944	33	23.2 [d]	
	U6	5	Oct.1944	33	20.0 [d]	
Buffalo grass--good uniform stands, unclipped, established by solid sodding in spring, 1940 [b]	1E	1	Sep.1942	3.5	711	-
	2E	2	Sep.1942	3.1	690	-
	4E	4	Aug.1942	2.7	619	-
	5B	5	Aug.1942	3.7	636	-
	6B	6	Aug.1942	2.9	695	-
	7E	7	Aug.1942	3.4	764	-
	10F	10	Aug.1942	3.5	577	-
Blue grama grass--good uniform stands, unclipped, established by solid sodding in spring, 1940 [b]	1D	1	Sep.1940	10.7	-	19.0
	2D	2	Sep.1940	16.4	-	21.4
	4B	4	Sep.1940	12.3	-	18.1
	7F	7	Sep.1940	11.9	-	12.1
	10D	10	Aug.1940	11.7	-	15.9
Alfalfa--good uniform stands, unclipped, established from seed in spring, 1942 [b]	2C	2	Sep.1943	12.9	101	-
	4B	4	Sep.1943	9.6	129	-
Native grass mixture--good stands of tall and short grasses, unclipped. Grasses include little bluestem, blue grama, and other short native grasses, established from seed in spring, 1942 [b]	1D	1	Sep.1943		147	-
	4D	4	Sep.1943		115	-
	7B	7	Sep.1943		151	-
Lespedeza sericea--good uniform stands, established from seed in May, 1939 [c]	B2-14B	3	June 1940	16	135	-
	B2-10B	3	June 1941	22	80	-

[a] Experiments in 3-ft width flat-bottomed channels at Stillwater Hydraulic Laboratory, Soil Conservation Service Research Project OK-R-3, Stillwater, Oklahoma.

[b] Experiments in 2-ft width flat-bottomed channels by Oklahoma Agricultural and Mechanical College Agricultural Experiment Station, Stillwater, Oklahoma.

[c] Experiments in 2-ft width flat-bottomed channels at Outdoor Hydraulic Laboratory, Soil Conservation Service Research Project SC-R-2, Spartanburg, South Carolina.

[d] Per cent occupancy, determined by line interception method.

The product of velocity and depth has been shown by REE and PALMER [1946] to be a satisfactory criterion for judging the hydraulic behavior and estimating n where the flow is through and over a vegetation-covered slope. This finding has been substantiated by a series of tests of unclipped Buffalo grass on slopes varying from one to ten per cent. The densities and lengths of cover were quite similar, and no adjustments were made. The excellent n-VD relationship is shown in Figure 6. It is particularly convenient to continue to use the product VD for shallow overland flow analyses, since it represents the discharge per unit-width strip.

Figures 7 and 8 present results obtained from a number of vegetative channel covers differing widely in physical structure and manner of growth. The Bermuda and lovegrass data, Figure 7, are particularly complete, extending to a unit-width discharge as low as 0.001 cubic foot per second. This is equivalent to a rate of runoff of only 0.43 inch per hour from a strip one foot wide

Table 2--Results of experiments

Channel	Test	Discharge per ft of width	Average depth, D	Mean velocity, V	Effective slope, S_e	Vegetation submergence	MANNING'S n
		c f s	ft	ft per sec	ft per ft	per cent	
				Bermuda grass			
U1	1	0.00113	0.0168	0.0669	0.0503	0	0.329
	2	.00276	.0304	.0912	.0504	0	.358
	3	.00630	.0490	.128	.0503	0	.347
	4	.0129	.076	.170	.0502	0	.350
	5	.0263	.124	.212	.0502	0	.389
	6A	.0428	.168	.255	.0502	10	.396
U2	1	0.00101	0.0124	0.0814	0.0502	0	0.220
	2	.00254	.026	.0976	.0503	0	.297
	3	.00616	.046	.134	.0504	0	.325
	4	.0124	.074	.168	.0506	0	.353
	5	.0287	.130	.221	.0506	0	.390
	6	.0474	.186	.255	.0506	0	.428
	7	.120	.325	.370	.0496	30	.424
U3	1	0.00109	0.0186	0.0586	0.0511	0	0.401
	2	.00292	.0272	.108	.0510	0	.280
	3	.00580	.042	.138	.0510	0	.296
	4	.0149	.076	.196	.0510	0	.309
	5	.0283	.117	.242	.0510	0	.332
	6	.0493	.176	.280	.0510	0	.376
	7	.0931	.266	.350	.0504	20	.396
				Weeping lovegrass			
U5	1	0.00148	0.0151	0.0978	0.0502	0	0.209
	2	.00310	.0228	.136	.0502	0	.196
	3	.00620	.0378	.164	.0502	0	.230
	4	.0138	.059	.234	.0500	0	.217
	5	.0274	.091	.301	.0500	0	.224
	6	.0442	.117	.378	.0500	0	.210
	6A	.0606	.140	.433	.0498	0	.208
	7	.114	.205	.556	.0498	0	.208
	8	.228	.323	.706	.0498	2	.222
	9	.432	.454	0.952	.0496	10	.205
	10	.650	.542	1.20	.0494	40	.183
U6	1	0.00142	0.0157	0.0902	0.0502	0	0.231
	2	.00315	.0228	.138	.0502	0	.194
	3	.00798	.0350	.228	.0502	0	.156
	4	.0148	.0483	.307	.0502	0	.144
	5	.0289	.0750	.385	.0503	0	.154
	6	.0442	.0998	.443	.0504	0	.162
				Buffalo grass			
1E	1	0.0212	0.123	0.172	0.0107	0	0.219
	3	.117	.321	.364	.0093	75	.185
2E	1	0.0180	0.103	0.175	0.0206	0	0.267
	2	.0379	.185	.205	.0203	10	.334
	3	.0630	.225	.280	.0199	50	.277
4E	1	0.0144	0.062	0.233	0.0383	0	0.198
	2	.0353	.111	.318	.0384	20	.213
	3	.0917	.165	.556	.0386	50	.159
5B	1	0.0179	0.077	0.232	0.0515	0	0.268
	2	.0478	.143	.334	.0513	10	.277
	3	.108	.187	.577	.0511	50	.192

Table 2--Results of experiments (Concluded)

Channel	Test	Discharge per ft of width	Average depth, D	Mean velocity, V	Effective slope, S_e	Vegetation submergence	MANNING'S n
		cfs	ft	ft per sec	ft per ft	per cent	
				Buffalo grass			
6B	1	0.0130	0.059	0.221	0.0604	0	0.253
	2	.0362	.115	.315	.0606	10	.276
	3	.0750	.159	.472	.0606	30	.228
7E	1	0.0184	0.082	0.225	0.0689	0	0.329
	2	.0367	.118	.311	.0688	0	.302
	3	.0790	.167	.473	.0689	30	.251
10F	1	0.0206	0.072	0.286	0.101	0	0.286
	2	.0468	.113	.414	.102	10	.268
	3	.103	.151	.684	.102	40	.197
				Blue grama grass			
1D	1	0.0523	0.218	0.240	0.0109	0	0.235
	2	.543	.778	.698	.0122	30	.198
2D	1	0.0682	0.232	0.294	0.0201	0	0.271
	2	.510	.788	.647	.0214	95	.285
4B	1	0.0628	0.152	0.413	0.0412	0	0.210
	2	.533	.503	1.06	.0415	80	.181
7F	1	0.0568	0.105	0.541	0.0713	0	0.163
	2	.516	.377	1.37	.0717	50	.152
				Alfalfa			
2C	1	0.0325	0.142	0.229	0.0200	0	0.250
	2	.0811	.251	.323	.0197	0	.257
	3	.188	.403	.466	.0191	0	.241
	4	.372	.583	.639	.0191	10	.225
4B	1	0.0533	0.143	0.373	0.0381	0	0.214
	2	.110	.243	.452	.0379	0	.251
	3	.250	.404	0.619	.0372	30	.257
	4	.521	.506	1.03	.0370	50	.178
				Native grass mixture			
1D	1	0.0366	0.167	0.219	0.0095	0	0.200
	2	.0876	.293	.299	.0100	0	.218
	3	.153	.447	.342	.0107	0	.265
	4	.309	.600	.515	.0112	20	.220
	5	.597	.765	.780	.0127	50	.183
4D	1	0.0609	0.183	0.333	0.0375	0	0.281
	2	.179	.391	.457	.0368	0	.337
	3	.365	.542	0.674	.0368	10	.281
	4	.815	.668	1.22	.0379	40	.180
7B	1	0.0376	0.113	0.333	0.0717	0	0.287
	2	.134	.232	.580	.0716	0	.260
	3	.265	.341	0.777	.0713	20	.249
	4	0.495	.438	1.13	.0713	30	.203
	5	1.11	.598	1.86	.0721	50	.153
				Lespedeza sericea			
B2-14B	1	0.370	0.534	0.693	0.0326	0	0.254
	2	0.566	.665	0.852	.0312	5	.234
	3	1.07	.762	1.40	.0311	90	.156
B2-10B	1	0.287	0.348	0.824	0.0279	0	0.149
	2	.499	.538	0.927	.0299	0	.183
	3	.937	.721	1.30	.0320	30	.164

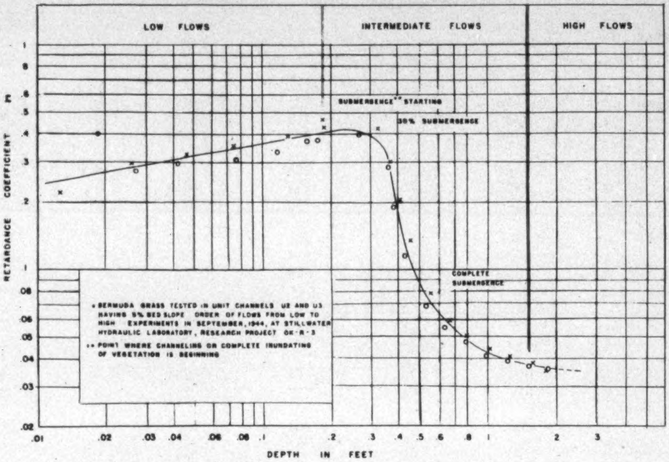

Fig. 5--Hydraulic behavior of a medium length sod-forming grass

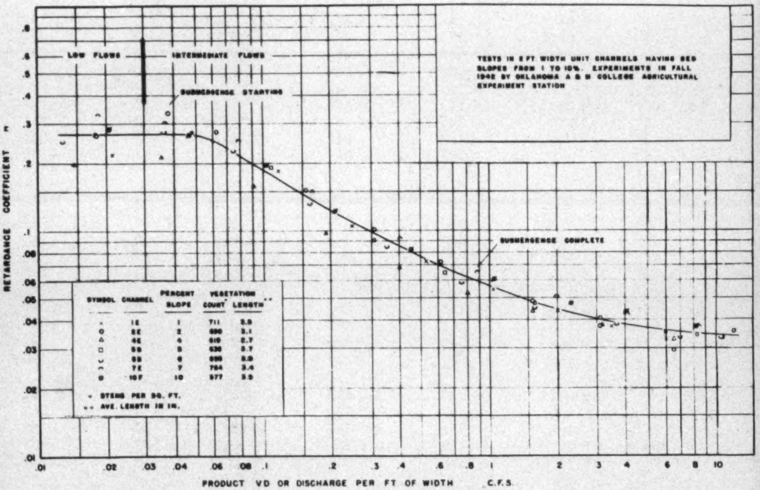

Fig. 6--Relationship of retardance-coefficient to discharge per unit-weight for good uniform stand, unclipped of buffalo grass

Table 3--Retardance coefficients for flow through several kinds of vegetation and limiting unit-width discharges

Description of covers used in tests	Value of MANNING'S n at point where unit-width discharge was sufficient to produce submergence	Unit-width discharge
Bermuda grass--dense, uniform cover, length 4-8 in, green, one year's growth	0.41	0.06
Weeping lovegrass--good stand from broadcast seeding in spring 6 months previous, length greater than 30 in, green	.21	.13
Buffalo grass--dense, uniform cover, length 2.5-3.5 in, green	.27	.03
Blue grama grass--good uniform stand of unclipped grass, average length 12 in, green	.24	.2
Native grass mixture--good stand of tall and short grasses, green	.26	.2
Alfalfa--good uniform stand, uncut, average length 11 in, green	.25	.2
Lespedeza sericea--good uniform stand, uncut, average length 19 in, green	.20	.4

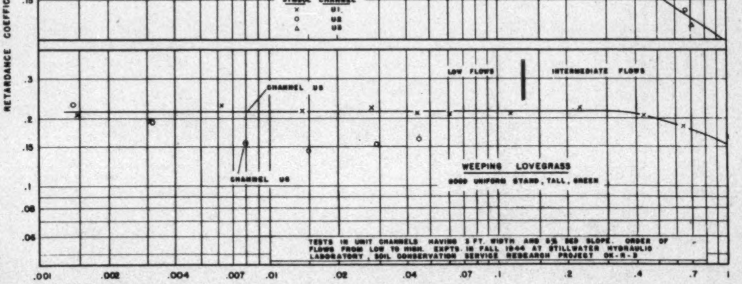

Fig. 7--Relationship of retardance coefficient to discharge per unit width for Bermuda grass and weeping lovegrass

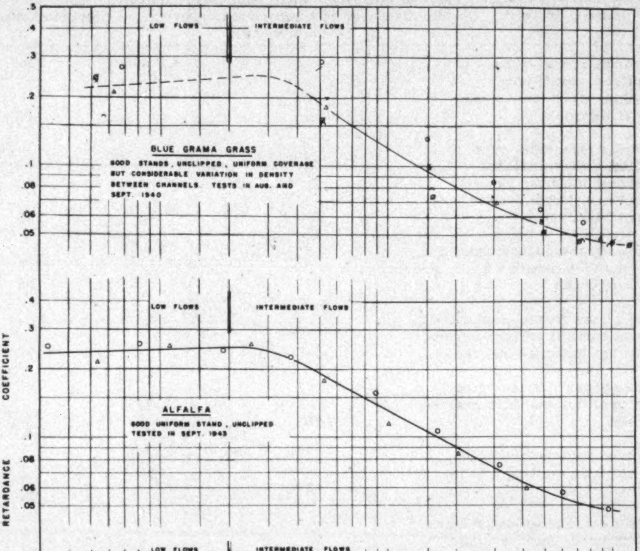

Fig. 8--Relationship of retardance-coefficient to discharge per unit-width for a number of vegetations and 100 feet long. These data extend well into the range of runoff from natural rainfall.

Note in Figures 7 and 8 the general tendency for n to increase with unit-width discharge up to and somewhat beyond the point where excessive bending and complete inundation of the plants first occur. This is most likely due to greater boundary resistance resulting from increase in foliage with depth and to greater area displacement by the vegetation. The highest n values (except for very shallow flows through a dense surface mulch) generally occur when the vegetation is partially bent over and is oscillating in the flow. Maximum boundary resistance then develops.

Table 3 summarizes the graphically presented n-discharge data. For field-application purposes the value of MANNING'S n at the top of the low flow range is given. This is probably not unreasonably conservative, since the covers tested were only recently established and no appreciable surface mulch had had time to develop. The effect of a mulch decreases with depth of flow and ordinarily would probably not have much influence on n at the stage where bending and submergence begin. Unit-width discharges greater than those in Table 3 result in significant bending and soon complete inundation, and thus in rapid reduction in n. Discussion of the n-discharge relationship in the intermediate and high flow ranges will not be presented here. Such a discussion and a method of field application are presented in a forthcoming publication [REE and PALMER, 1946]. A practical observation on the results in Table 3 is the similarity of the value of n for all the kinds of vegetation represented except Bermuda grass.

IZZARD [1944] reported overland-flow results from Kentucky bluegrass plots subjected to simulated rainfall of 1.83 and 3.81 inches per hour. The values of n determined to apply under these rainfall intensities were 0.43 and 0.52, respectively. The value for n for a dense turf and its increase with depth of flow (which the higher intensity produced) are consistent with the experimental results presented here.

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RADIAL FLOW IN A LEAKY ARTESIAN AQUIFER

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Abstract--A partial differential equation is set up for radial flow in an elastic artesian aquifer into which there is vertical leakage in proportion to the drawdown. This differential equation is integrated to obtain two steady state solutions, one for the case of a well in an infinite aquifer, and the other for the case where the head is maintained constant along an outer boundary concentric with the well. In the second case, the solution of the non-steady state is also obtained for flow towards a well discharging at a steady rate, the initial state being one of uniform head distribution. A table and some curves are given for one set of assumed values of three of the parameters of the system.

Introduction--The theory of an elastic artesian aquifer [see "References" at end of paper, JACOB, 1940] has in general proved successful in dealing with the non-steady flow of water in actual artesian beds. It is framed on the hypothesis that "a specific amount of water is discharged instantaneously from storage (within the aquifer) as the pressure falls" [THEIS, 1945]. In other words, the water-producing bed is idealized as a perfectly elastic aquifer confined between parallel impermeable planes. As the head declines, the water expands and the aquifer is compressed. As the head is restored, the water is compressed and the aquifer expands, assumedly with no permanent loss of volume.

The volume of water released from "storage" within an elastic aquifer is proportional to the decline of head and to the "storage coefficient" (S). This coefficient is the product of the thickness of the bed, m, and the relative volume of water released from storage by a unit decline of head. That is,

$$S = m(dV_w/ds)/V \qquad (1)$$

where dV_w is the small volume of water released from storage within the volume V. The small decline of head is ds. Taking into account the porosity, θ, of the bed, $V = V_w/\theta$. Making this substitution and replacing ds by its equivalent $(-dp/\gamma)$, p being pressure and γ the specific weight of the water,

$$S = \gamma\,\theta\, m(-dV_w/V_w dp) \qquad (2)$$

or

$$S = \gamma\theta m\beta' \qquad (3)$$

The quantity in parentheses in equation (2), symbolized by β' in equation (3), is the apparent compressibility of the water, which includes the actual compressibility of the water, β, and the compressibility of the solid "skeleton" of the aquifer itself. Experience has shown [GUYTON, 1941; JACOB, 1941] that β' is generally several times as large as β.

The storage coefficient is to be determined empirically from observations of the rate of decline of head produced by pumping. In practice minor departures from the elastic theory are absorbed into this empirical coefficient. More serious departures generally are reflected in a systematic variation of S with time.

Commonly an artesian aquifer is confined by beds, one or both of which may be semi-permeable and which may therefore permit leakage to occur. This principle was recognized by CHAMBERLIN [1885] in his paper on the "requisite and qualifying conditions of artesian wells," and was later elaborated upon somewhat by FULLER [1905, 1908] who cited unusual examples showing that a confining bed is not always a requisite for artesian flow. CHAMBERLIN'S ideas regarding leakage through confining beds were confirmed by the work of DARTON and others [NORTON, 1912] in Iowa, and of MEINZER [1911] in the drift area of southern Minnesota.

An artesian bed resting on an impermeable base at relatively shallow depth may be overlain by a semi-pervious "clay" or silt in which the ground-water is continuously being replenished by rainfall and in which a more or less uniform head is maintained supplying the leakage that is induced by the lowering of artesian head. This condition is found in the polder areas of Holland where the problem was first submitted to analysis by DE GLEE [1930], STEGGEWENTZ and VAN NES [1939], and others. Very commonly the semi-pervious confining bed is in turn overlain by another sand, with a capacity for lateral flow sufficient to maintain essentially constant head in spite of the downward leakage into the underlying artesian sand. This situation is illustrated diagrammatically by Figure 1.

Upward leakage through a semi-pervious bed from a second artesian sand underlying the first gives rise to the same physical problem, as does a combination of leakage from above and below. In either case the semi-confined condition may be effected on a large scale by lenticular zones in which clays predominate, as in many coastal plain deposits, rather than by a single well-defined layer.

To describe the flow more precisely under these various conditions, it is necessary to modify the elastic theory to take leakage into account. Fortunately, however, the same mathematical model may be applied to the several examples cited. For convenience in developing the theory, the simple case shown in Figure 1 is chosen.

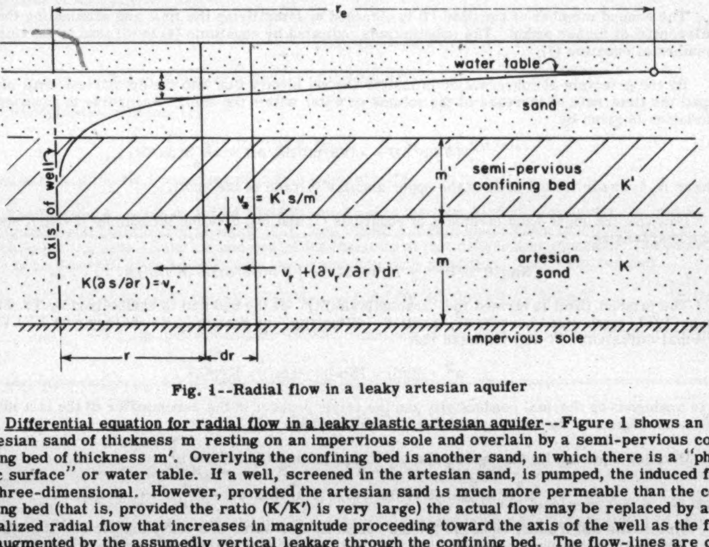
r_e
water table
sand
s
m'
semi-pervious confining bed
K'
axis of well
$v_s = K's/m'$
m
artesian sand
K
$K(\partial s/\partial r) = v_r$
$v_r + (\partial v_r/\partial r)dr$
impervious sole
r
dr

Fig. 1--Radial flow in a leaky artesian aquifer

Differential equation for radial flow in a leaky elastic artesian aquifer--Figure 1 shows an artesian sand of thickness m resting on an impervious sole and overlain by a semi-pervious confining bed of thickness m'. Overlying the confining bed is another sand, in which there is a "phreatic surface" or water table. If a well, screened in the artesian sand, is pumped, the induced flow is three-dimensional. However, provided the artesian sand is much more permeable than the confining bed (that is, provided the ratio (K/K') is very large) the actual flow may be replaced by an idealized radial flow that increases in magnitude proceeding toward the axis of the well as the flow is augmented by the assumedly vertical leakage through the confining bed. The flow-lines are considered to be refracted a full right angle as they cross the contact between the artesian sand and its confining bed. Actually the tangents of the angles of incidence and refraction are in the same ratio as the respective permeabilities.

Consider the elemental cylindrical shell of inner radius r and thickness dr which is co-axial with the well. The flow per unit area through the inner cylindrical surface of that shell is

$$v_r = K(\partial s/\partial r) \qquad (4)$$

where s is the drawdown and K is the "permeability" or transmission constant (defined as "the quantity [volume] of water that would be transmitted in unit time through a cylinder of the soil of unit length and unit cross section under unit difference in head at the ends"[SLICHTER, 1899]. Similarly the flow per unit area through the outer cylindrical surface is

$$v_r + (\partial v_r/\partial r)\,dr = K[(\partial s/\partial r) + (\partial^2 s/\partial r^2)\,dr] \ldots\ldots\ldots\ldots\ldots (5)$$

The flow per unit area through the upper bounding plane of the aquifer is

$$v_z = K's/m' \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where K' is the transmission constant of the semi-pervious confining bed. The z is taken positive downwards.

Multiplying each of these by the respective surface areas and combining, one gets for the net inward flux into the cylindrical shell

$$\begin{aligned} &2\pi r m v_r - 2\pi m(r + dr)[v_r + (\partial v_r/\partial r)\,dr] + 2\pi r v_z dr = \\ &= 2\pi r dr[-(m v_r/r) - m(\partial v_r/\partial r) + v_z] = \\ &= 2\pi r dr[-(Km/r)(\partial s/\partial r) - Km(\partial^2 s/\partial r^2) + (K'/m')s] \ldots\ldots\ldots\ldots (7) \end{aligned}$$

The second member of equation (7) is obtained by simplifying the first and eliminating the differential of higher order. The substitutions indicated by equations (4) to (6) lead to the third member of equation (7).

By the principle of conservation of matter the net inward flux into the cylindrical shell must equal the time rate of increase of the volume of water within the shell. According to equation (1) the latter is given by

$$-(\partial V_w/\partial t) = -(VS/m)(\partial s/\partial t) = -A_z S(\partial s/\partial t) \ldots\ldots\ldots\ldots (8)$$

where A_z ($=2\pi r dr$) is the area of the upper annular surface of the shell.

Equating the right-hand members of equations (7) and (8), dividing through by ($2\pi r dr$), and then rearranging,

$$Km[(\partial^2 s/\partial r^2) + (1/r)(\partial s/\partial r)] = S(\partial s/\partial t) + (K'/m')s \ldots\ldots\ldots\ldots (9)$$

The product (Km) is termed the "transmissibility" of the bed and is symbolized by T. The ratio (T/S), symbolized here by a^2 is called "diffusivity" by reason of its analogy with KELVIN'S thermal diffusivity. It may be noted that

$$a^2 = (T/S) = (Km)/(\gamma\theta m\beta') = K/\gamma\theta\beta' \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

K is analogous to thermal conductivity and the triple product in the denominator of the last member is analogous to thermal capacitance per unit volume.

Dividing equation (9) through by Km or T, and putting $(K'/m'S) = b^2$,

$$(\partial^2 s/\partial r^2) + (1/r)(\partial s/\partial r) = (1/a^2)(\partial s/\partial t) + (b^2/a^2)s \ldots\ldots\ldots\ldots (11)$$

This is the differential equation for the radial flow of water in a leaky elastic artesian aquifer. To find a particular solution that is useful it is first necessary to formulate the problem by specifying the boundary conditions that are to be satisfied.

Steady-state solutions--If the flow remains unchanged with time, $(\partial s/\partial t) = 0$, and a permanent or steady state is said to exist. Then the differential equation is

$$(\partial^2 s/\partial r^2) + (1/r)(\partial s/\partial r) - (b^2/a^2)s = 0 \ldots\ldots\ldots\ldots\ldots (12)$$

A simple problem,yet one of practical interest is that of determining the drawdown produced by a well discharging at a steady rate from an infinite aquifer. The well can conveniently be idealized as a mathematical sink. The drawdown at infinity is zero. As the sink is approached the gradient increases in such fashion that $2\pi r T(\partial s/\partial r) \rightarrow -Q$, Q being the discharge of the well. In this case, then, the boundary conditions are

$$\left.\begin{array}{l} s \to 0 \text{ as } r \to \infty \\ \lim\limits_{r \to 0} r(\partial s/\partial r) = -Q/2\pi T \end{array}\right\} \tag{13}$$

The solution [STEGGEWENTZ and VAN NES, 1939; ANONYMOUS, 1939] is found to be

$$s = C \cdot K_0(br/a) \tag{14}$$

where C is a constant whose value is to be determined from the second of equations (13), and K_o is the modified BESSEL function of the second kind of zero order, which satisfies equation (12). As r becomes infinite the K_o approaches zero, satisfying the first boundary condition. As r approaches zero the slope of K_o approaches the negative reciprocal of its argument. Therefore, $C = Q/2\pi T$, and

$$s = (Q/2\pi T)K_0(br/a) \tag{15}$$

Another problem of interest is that of a steadily discharging well (idealized as a sink) in the center of a circular aquifer along whose outer boundary the head remains constant. The boundary conditions of this problem are

$$\left.\begin{array}{l} s = 0, \; r = r_e \\ \lim\limits_{r \to 0} r(\partial s/\partial r) = -Q/2\pi T \end{array}\right\} \tag{16}$$

Here r_e is the radius of the outer boundary of the aquifer.

To obtain the solution, try

$$s = C[I_0(br_e/a)K_0(br/a) - K_0(br_e/a)I_0(br/a)] \tag{17}$$

which satisfies the first boundary condition (equations 16).

The function I_0 is the modified BESSEL function of the first kind of zero-order. I_0 and K_0 are fundamental solutions of equation (12). Any linear combination of these functions, such as in equation (17), is also a solution because of the linearity of that differential equation. The constant C is to be determined so as to satisfy the second boundary condition. This requires that

$$-CI_0(br_e/a)\lim_{r \to 0}[(br/a)K_1(br/a)] - CK_0(br_e/a)\lim_{r \to 0}[(br/a)I_1(br/a)] = -Q/2\pi T \tag{18}$$

I_1 and K_1 are first-order modified BESSEL functions of the first and second kinds, respectively.

The first limit in equation (18) is unity and the second zero. Therefore

$$C = (Q/2\pi T)/I_0(br_e/a) \tag{19}$$

and

$$s = (Q/2\pi T)[K_0(br/a) - K_0(br_e/a)\,I_0(br/a)/I_0(br_e/a)] \tag{20}$$

A graph of this equation is given in Figure 2 for $r_e = 100{,}000$ ft and $(a/b) = 20{,}000$ ft. In making these and other computations, the tables of the British Association for the Advancement of Science [ANONYMOUS, 1937] have proved very useful.

Non-steady state solution--A practical problem is that of determining the variable drawdown produced by a well starting from rest and discharging at a steady rate thereafter. At a distance r_e, equal to the radius of the outer circular boundary, the head is assumed to remain constant. Initially the drawdown is uniformly zero throughout the aquifer. The problem is to determine the variation of the drawdown with time at a given distance from the well. For convenience the solution will be broken up into two parts, a steady-state solution, s, and a transient solution, s′, the combined solution satisfying the boundary conditions

$$\left.\begin{array}{l} (s + s') = 0, \; t = 0 \\ (s + s') = 0, \; r = r_e \\ \lim\limits_{r \to 0} r[\partial(s + s')/\partial r] = -Q/2\pi T \end{array}\right\} \tag{21}$$

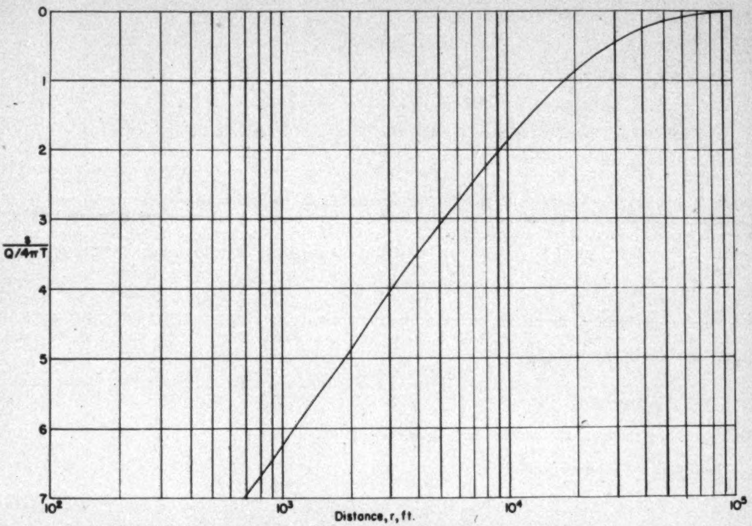

Fig..2--Ultimate distribution of drawdown in a leaky artesian aquifer, where $r_e = 100{,}000$ feet, $T = 20{,}000$ square feet per day, and $(a/b) = 20{,}000$ feet

The steady-state solution in question is the one given by equation (20), which, it will be recalled, satisfies the differential equation (12) and the boundary equations (16). Comparing those boundary conditions with the ones given by equations (21) it is seen that the boundary conditions of the transient problem are

$$\left.\begin{aligned} s' &= -(Q/2\pi T)[K_0(br/a) - K_0(br_e/a)\,I_0(br/a)/I_0(br_e/a)],\ t = 0 \\ s' &= 0,\ \ r = r_e \\ \lim_{r\to 0} r\,(\partial s'/\partial r) &= 0 \end{aligned}\right\} \ldots\ldots\ldots \quad (22)$$

The transient solution may be obtained by assuming that it will be in the form

$$s' = R(r)\cdot T(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

where R is a function that is independent of t and T is another function (not to be confused with transmissibility) that is independent of r. Proceeding on this postulate equation (11) becomes

$$T[(\partial^2 R/\partial r^2) + (1/r)(\partial R/\partial r)] = R[(1/a^2)(\partial T/\partial t) + (b^2/a^2)\,T] \ldots\ldots\ldots\ldots (24)$$

Dividing equation (24) through by RT one gets on the left-hand side a function of the single variable r, and on the right-hand side a function of the other variable t. These can be equated only provided they are equal to some constant, $-\alpha^2$. Thus

$$(1/R)[(\partial^2 R/\partial r^2) + (1/r)(\partial R/\partial r)] = -\alpha^2 = (1/a^2 T)(\partial T/\partial t) + (b/a)^2 \ldots\ldots\ldots\ldots (25)$$

From the first two members of equation (25) one has

$$(\partial^2 R/\partial r^2) + (1/r)(\partial R/\partial r) + \alpha^2 R = 0 \ldots\ldots\ldots\ldots (26)$$

A fundamental solution of this equation is

$$R = A \cdot J_o(\alpha r) \quad \ldots\ldots (27)$$

where A is a constant whose value is to be determined from the boundary conditions. J_o is the BESSEL function of the first kind of zero order.

From the last two members of equation (25) one has

$$(\partial T/\partial t) = -(\alpha^2 a^2 + b^2)\,T \quad \ldots\ldots (28)$$

A solution of this equation is

$$T = e^{-(\alpha^2 a^2 + b^2)t} \quad \ldots\ldots (29)$$

Substituting in equation (23) from equations (27) and (29), it is found that the transient solution of equation (11) is of the form

$$s' = A \cdot J_o(\alpha r)\, e^{-(\alpha^2 a^2 + b^2)t} \quad \ldots\ldots (30)$$

This satisfies the third boundary condition (equations 22), for $\partial[J_o(\alpha r)]/\partial r = -\alpha J_1(\alpha r)$ and $J_1(0) = 0$, J_1 being the BESSEL function of the first kind of the first order.

The second boundary condition is also satisfied by equation (30) provided α is so chosen that (αr_e) is a root of $J_o(\alpha r_e) = 0$. Actually there are an unlimited number of such roots, a typical one being designated $(\alpha_n r_e)$. Thus a solution of equation (11) which satisfies the second and third boundary conditions (equations 22) is

$$s' = \sum_{n=1}^{\infty} A_n J_o(\alpha_n r)\, e^{-(\alpha_n^2 a^2 + b^2)t} \quad \ldots\ldots (31)$$

When t = 0 the exponential becomes unity and equation (31) is thereby simplified. If the initial condition, given by the first of equations (22), is to be satisfied, then

$$\sum_{n=1}^{\infty} A_n J_o(\alpha_n r) = -(Q/2\pi T)[K_o(br/a) - K_o(br_e/a)\,I_o(br/a)/I_o(br_e/a)] \quad \ldots\ldots (32)$$

The A_n may be determined by multiplying both sides of equation (32) by $[rJ_o(\alpha_m r)dr]$ and integrating from 0 to r_e. When $m \neq n$, the integral of the left side is zero. When $m = n$, the integration of equation (32) yields

$$(A_n r_e^2/2)\,J_1^2(\alpha_n r_e) = -(Q/2\pi T)/[\alpha_n^2 + (b/a)^2] \quad \ldots\ldots (33)$$

Solving for A_n

$$A_n = -(Q/\pi T)/\left\{(\alpha_n r_e)^2 J_1^2(\alpha_n r_e)[1 + (b/\alpha_n a)^2]\right\} \quad \ldots\ldots (34)$$

Substituting in equation (31) the value of A_n given by equation (34),

$$s' = -(Q/\pi T)\sum_{n=1}^{\infty}[J_o(\alpha_n r)\, e^{-(\alpha_n^2 a^2 + b^2)t}]/\left\{(\alpha_n r_e)^2 J_1^2(\alpha_n r_e)[1 + (b/\alpha_n a)^2]\right\} \quad \ldots\ldots (35)$$

This is the transient solution which is to be combined with the steady-state solution obtained in the preceding section, giving

$$s = (Q/2\pi T)\left\{[K_o(br/a) - K_o(br_e/a)\,I_o(br/a)/I_o(br_e/a)] - 2\Sigma\right\} \quad \ldots\ldots (36)$$

in which Σ is an abbreviation for the summation indicated in equation (35).

To recapitulate, equation (36) gives the drawdown at time t and at a distance r from a well of constant discharge Q at the center of a circular aquifer of radius r_e. The drawdown is initially zero over the entire aquifer and remains zero along the outer boundary ($r = r_e$). The discharge of the well begins at t = 0.

Figure 3 gives curves computed from equation (36) with r_e = 100,000 ft, T = 20,000 sq ft per day, and (a/b) = 20,000 ft. The drawdown is plotted in units of $(Q/4\pi T)$. For comparison the drawdown curve for an elastic aquifer without leakage is given. The function W(u) is the negative exponential integral of a negative argument, which for small values of u may be approximated by a logarithmic term minus EULER'S constant, as indicated in Figure 3. The reciprocal of the abscissa

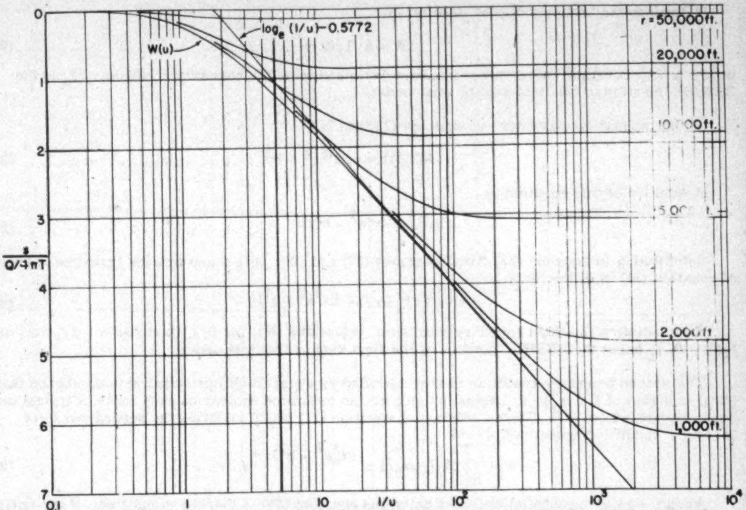

Fig. 3--Time drawdown curves for leaky artesian aquifer with well at center discharging at rate Q. Drawdown is 0 at $r_e = 100{,}000$ feet. T = 20,000 square feet per day, and (a/b) = 20,000 feet

is $u = r^2S/4Tt$, whence $(1/u) = 4Tt/r^2S$.

The data on which Figure 3 is based are given in the Table 1. As time becomes great, $u \rightarrow 0$ and the steady-state distribution is realized. Values of steady state drawdown (nondimensional, from equation 20) are given in the first line in the body of the table. For smaller values of time u increases correspondingly. Sufficient points on the non-steady time drawdown curves are given to aid in plotting those curves on semi-logarithmic coordinates.

From data on the steady state distribution of drawdown in the vicinity of a well or a center of pumping, if leakage is known to occur, values of the parameters T and (a/b) may be determined by a modification of the THEIS [JACOB, 1940, p. 582] graphical method, in which the "type curve" is a plot of $K_0(x)$ against x on logarithmic paper and the observational data are plotted on logarithmic paper of the same scale with r as abscissa and s as ordinate.

The value of the storage-coefficient, S, may be determined by application of the THEIS method in the usual manner to drawdowns observed during the early phase of the transient state. Simultaneously the value of T may be checked.

Just as with the theory of simple elastic aquifers, so not only does the theory presented here permit the determination of an additional parameter (the leakage) of an artesian system, but it also allows the prediction of drawdowns under conditions of operation different from those observed to determine that parameter. Thus is taken another step forward in the construction of useful mathematical models of confined ground water systems.

Table 1--Values of $s/(Q/4\pi T)$

u	Distance, r, in feet					
	1,000	2,000	5,000	10,000	20,000	50,000
0	6.228	4.854	3.083	1.849	0.842	0.124
0.0002	6.217	....	....	....	....	....
0.0005	6.082	....	....	....	....	....
0.001	5.796	4.829	....	....	....	....
0.002	5.354	4.708	....	....	....	....
0.005	4.608	4.296	3.072	....	....	....
0.01	3.980	3.815	2.993	....	....	....
0.02	....	3.245	2.766	1.838	....	....
0.05	....	....	2.230	1.708	....	....
0.1	....	....	1.715	1.443	0.819	....
0.2	....	....	....	1.060	0.715	....
0.5	....	....	....	0.521	0.421	0.117
1.	....	....	....	....	0.186	0.080
2.	....	....	....	....	....	0.027

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U. S. Geological Survey,
Washington, D. C.

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DISCUSSION

DON KIRKHAM (Naval Ordnance Laboratory, Washington, D. C., October 1, 1945)--This paper is a valuable contribution to the theory of hydrology. The mathematical development involves theory unfamiliar to many hydrologists, and for this reason in the discussion it is the purpose to point out aids in following the mathematics, and also to discuss the final equation in some detail, as it is believed that this equation involves much more than a reader will appreciate without considerable thought.

The basic functions used in the solution of the author's problem are the BESSEL-functions J_0, J_1, I_0, I_1, K_0, and K_1, the notation being that used in his reference [ANONYMOUS, Mathematical tables, v. 6, British Assoc. for the Advancement of Science, Cambridge Univ. Press, 1937]. One of the best discussions covering essential points, and using the same notation as that employed by the author, is found in W. R. SMYTHE'S "Treatise on dynamic and static electricity," (McGraw-Hill, New York, 1939), pp. 168-196. McLACHLAN'S "Bessel functions for Engineers," (Oxford, 1934), is also valuable, for in it the reader will find that the use of equation (108) on page 164, and equation (132) on page 166, makes easy the verification of the author's equations (33) and (34).

As an example of the above functions - and since there will be occasion to refer to them later - the functions I_0 and K_0 will be given here. They are

$$I_0(x) = 1 + x^2/2^2\,(1\,!)^2 + x^4/2^4\,(2\,!)^2 + x^6/2^6\,(3\,!)^2 + \ldots \quad \ldots\ldots \quad (1)$$

$$\begin{aligned} K_0(x) = -[\gamma + \log_e(x/2)]\, I_0(x) &+ (1/1\,!)^2(x/2)^2 \\ &+ (1/2\,!)^2(x/2)^4(1+1/2) \\ &+ (1/3\,!)^2(x/2)^6(1+1/2+1/3) + \ldots \quad \ldots \quad (2) \end{aligned}$$

In the last expression, γ is the usual EULER constant having the value 0.5772 to four places of decimals. This constant appears in the definition of a number of functions, for example, in the definition of the exponential integral functions, equation (4).

In connection with equation (36) of the author, giving the final result, it will first be pointed out that in the steady state ($t=\infty$) the equation shows the flow to be independent of the elasticity.

In the steady state, equation (36) reduces to equation (20). Now since, $a^2 = Km/S = T/S$ and $b^2 = K'/m'S$, although b and a each involves the elasticity constant S, their ratio--the only manner in which b and a occur in equation (20)--does not. In fact, $b/a = (K'/Kmm')^{1/2}$. Thus in the steady state the drawdown-curve, equation (20), is independent of the elasticity. The theory therefore indicates that in the steady state two aquifers having K, K', m, m', Q, T, and r_e all equal will have identical drawdown curves regardless of what the elasticity constants of these aquifers may be.

It is next shown that when $t=\infty$ (again the steady state) and, in addition, the overlying clay is strictly impermeable, equation (36) reduces to a well-known result. It is necessary in this case to determine the value of the right-hand side of equation (36) when $b=0$.

Substituting $b=0$ in equation (36) the result, $s = 0$, an obviously erroneous answer, is obtained. The corrrect result is obtained by letting b approach zero, whereby it is seen from equations (1), (2), and the author's equation (36) that

$$\lim_{b\to 0} s = (Q/2\pi T)\Big\{-[\gamma + \log_e(br/a)] + [\gamma + \log_e(br_e/a)]\Big\}$$

that is,

$$s = (Q/2\pi T)\log_e(r_e/r), \text{leakage zero, steady state} \quad \ldots\ldots\ldots\ldots \quad (3)$$

the familiar result sought (see MUSKAT, "The flow of homogeneous fluids through porous media," (McGraw-Hill, pp. 150-154, 1937).

In order to determine next what happens in the steady state ($t=\infty$) when the leakage is finite ($b>0$), but when the extent of the aquifer is very large, ($r_e\to\infty$), the following relations (found in treatises on BESSEL-functions) are needed:

$$\underset{x\to\infty}{K_0(x)} = (\pi/2x)^{1/2}\, e^{-x}$$

$$\underset{x\to\infty}{I_0(x)} = (1/2\pi x)^{1/2}\, e^{x}$$

Using these in equation (36) it is found that

$$\lim_{r_e \to \infty} s = (Q/2\pi T)\,[K_0(br/a) - I_0(br/a)\cdot \pi e^{-2br} e/a]$$

that is

$$s = (Q/2\pi T)\, K_0(br/a)\,, \quad r_e \to \infty$$

which is the steady state result for an infinite aquifer given by the author in equation (5). It is noted again that this result, since it contains b/a as a ratio, does not involve the elasticity of the aquifer.

So far, equation (36) has been considered for cases when $t=\infty$, that is, when the Σ terms are zero. The remainder of this discussion will be concerned with the solution of the non-steady state.

From physical intuition when the distances r from the well at which drawdown measurements are made are small compared to the extent of the aquifer, and when the elapsed time of pumping is small compared to the pumping time required to obtain the steady state, the drawdown should be the same for a leaky aquifer of finite extent as for a non-leaky aquifer ($b^2=0$) of infinite extent. That this is true may be seen in the author's Figure 2. It might also be expected that if two such aquifers (one of infinite extent and the other of finite extent r_e) each had zero leakage, the drawdown-curve would be the same for larger values of elapsed pumping time than when the aquifer of finite extent is leaky. I have prepared Figure 1 to bring out this point.

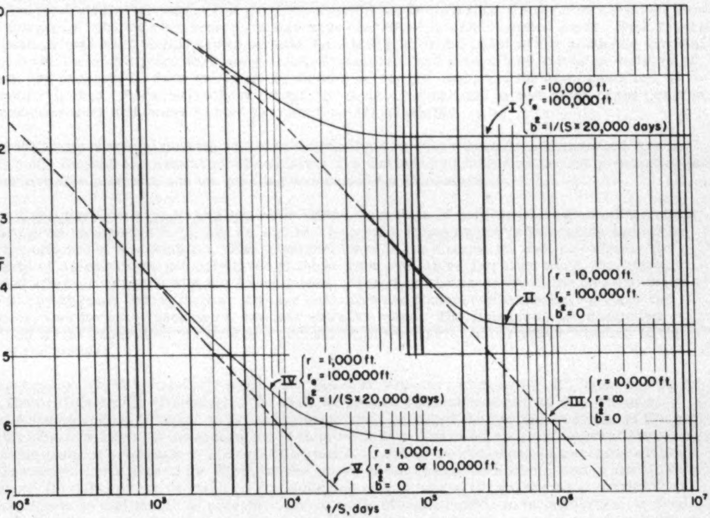

Fig. 1--Variation of drawdown with time

In Figure 1 (where the drawdown is plotted in units of $(Q/4\pi T)$, and the time as t in days divided by S), Curve I shows the variation of drawdown with time for $b^2 = 1/(20{,}000\ S\ ft)$ and $r_e = 100{,}000$ ft at a distance 10,000 ft from the well, and Curve II shows the drawdown for the same case except that now $b^2 = 0$. Curve III is the drawdown curve for the infinite non-leaky aquifer. It is seen that Curves I and III correspond up to about $t/S = 3\times 10^3$ days, whereas Curves II and III correspond up to about $t/S = 10^5$ days. Curves IV and V show results for r = 1000 ft. Curve V is equally valid for the case $r_e = \infty$, $b^2 = 0$, and the case $r_e = 100,000$ ft, $b^2 = 0$, insofar as the curve is contained on the paper. A calculation from equation (3) shows that the curve for r_e=100,000, $b^2 = 0$, does not become flat until $S/(Q/4\ \ T) = 9.21$. .

In Figure 1 the data for Curves I and IV are taken from the author's Figure 2, and Curves III and IV are calculated from the expression (where $u = r^2S/4Tt$)

$$s/(Q/4\pi T) = -\mathrm{Ei}(-u) = \int_u^\infty (e^{-y}/y)\,dy \quad .$$
$$= -0.5772 + \log_e(1/u) + u - u^2/2.2! + \ldots \quad \ldots\ldots\ldots (4)$$

the expression for drawdown in an infinte elastic aquifer of zero leakage given by the author in reference [1], and again mentioned near the end of his paper. In this paper, he uses the notation W(u) for the more conventional notation -Ei(-u), used in his paper of 1940. With regard to the function -Ei(-u), it may be noted that extensively tabulated values of -Ei(-u) are available in the Federal Works Project "Tables of Sine, Cosine, and Exponential Integrals," Vols. I and II, volumes not available when the author wrote his 1940 article.

A final point is noted. Although mathematically $s/(Q/4\pi T)$ appears to go to infinity (see the author's Figure 2 and curves III and V of Figure 1) when $t = \infty$; and also appears in equation (3) to go to infinity when $r_e \rightarrow \infty$; from physical considerations this cannot occur. Equation (36) of the author, of which equations (3) and (4) may be considered special cases, will, however, be valid for large values of r_e and/or t, if the parameter Q is small.

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THE MEETING OF THE EXECUTIVE COMMITTEE OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS, IN OXFORD, DECEMBER 10-14, 1945

H. S. J. L. Winterbotham

Foreword[1]

Papers laid before the Committee--(1) Report on the Proceedings of the Seventh (Washington) General Assembly; (2) report of the General Secretary for the war period; (3) notes on administration; (4) balance sheet of Union funds for the period January 1, 1939, to November 30, 1945; (5) recommendations on the future administration of the Union, made by the British National Committee in February 1945; (6) provisional agenda.

The position in the autumn of 1945--During the war the activities of the Union had not ceased. From the Union itself, or from the Associations whether in free or in occupied countries, funds were found for the maintenance of essential services. On the other hand intercourse, by letter as well as by personal visit, was impossible. Officers of the Union and of the Associations had died or been incapacitated. Presidents had been separated from Secretaries. In the free countries certain "Emergency" officers had been appointed to act for those in still occupied lands. Such reports as had been printed were hardly known outside the country of origin. Meanwhile academic circles, throughout the United Nations, were considering Committees and centralized action on matters of Education and of Science. Such bodies might directly affect the work, and the administration, of the Scientific Unions. It was urgently necessary to replace casualties, to take stock of the position, and to consider when and where to hold the next General Assembly.

The difficulty of travel, and the fact that most members of the Executive Committee live in Europe, made England the natural meeting place. The University Christmas recess provided opportunity for suitable quarters, and the meeting was called for December 10.

The Executive Committee as called--The statutory powers of the Executive Committee of the Union are given in Statutes 8, 11, 12, 14, and 18. Naturally it has no power to replace casualties among the officers of Associations. But seven members of the Committee are, ex-officio, the Presidents of Associations, and only three of these were available. Deputies were, therefore, nominated after consultation with the Associations. Moreover the presence of the General Secretaries, in closer touch during the war with the activities and finances of Associations than the Presidents, was obviously necessary, and they were co-opted. The circumstances demanded action, and it was imperative to summon a committee in the spirit, rather than according to the letter, of the Statutes.

The Agenda--(1) Elections, President and General Secretary (Statute 8); (2) time and place of next General Assembly (Statute 11); (3) shall we reopen subscription now or wait for next General Assembly, and, if we do, what subscription shall be asked for pending decision of General Assembly (By-Law 13); (4) consideration of Report on War Years by outgoing General Secretary; (5) consideration of proposals by National Committees, and of the decisions or recommendations of the Executive Committee of the ICSU, on the policy of the Unions as a whole, and of the IUGG in particular: (a) What do we do about (i) non-adhering countries and (ii) ex-enemy countries? (b) Is Convention to be diplomatic or private? (c) Is basis of subscription to be population or free choice of class? and (d) Statutes: (i) Do we stand by Edinburgh Statutes, as amended in detail or do we revive the proposed new Statutes as drafted by the last President? (ii) What alteration, if any, do we advise for consideration of General Assembly? (6) consideration of the affairs of the Associations; and (7) consideration of any other business.

The Agenda were not followed in strict accordance with these headings, but were often postponed for evening discussion among those most interested, and decided upon at some later meeting. In this report, however, the agenda sequence is followed.

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[1] Where Statutes or By-Laws are referred to in the text they can be consulted on pp. 97-109 of the Edinburgh report.

The Proceedings

Preliminary remarks--The General Secretary, who took the chair, referred to the deaths, not only of the late President Dr. LA COUR, but also of Dr. BOWIE, the previous President, and of Colonel Sir HENRY LYONS, the first General Secretary. After a few matters concerning the accommodation at the Colleges which were acting as hosts, and the times and places of discussion, the work of the meeting began.

[Note: Those in attendance at the Executive Committee meetings were: A. M. VIBERT (Hydrology) of France; JEAN ROTHÉ, (Seismology) of France; General G. PERRIER (Geodesy) of France; J. A. FLEMING (Terrestrial Magnetism and Electricity) of the United States; C. F. BAESCHLIN (Geodesy) of Switzerland; R. STONELEY (Volcanology) of Great Britain; A. H. R. GOLDIE (Terrestrial Magnetism and Electricity) of Great Britain; C. LACLAVÈRE (Hydrology) of France; J. E. RICHEY (Seismology) of Great Britain ; W. D. LAMBERT (Geodesy) of the United States; J. PROUDMAN (Oceanography) of Great Britain; B. HELLAND-HANSEN (Oceanography) of Norway; P. L. MERCANTON (Meteorology) of Switzerland; R. M. FIELD (Geodesy and Oceanography) of the United States; SYDNEY CHAPMAN (Meteorology, Terrestrial Magnetism and Electricity) of Great Britain; and H. S. J. L. WINTERBOTHAM (Geodesy) of Great Britain. Astronomer Royal, H. SPENCER JONES (Geodesy) of Great Britain was present for special Committee discussions on December 11.--Ed.]

Elections--The following elections were made: To be President, Professor B. HELLAND-HANSEN (the proposal came from Professor J. PROUDMAN, was seconded by Dr. J. A. FLEMING, and carried unanimously); to be General Secretary, Dr. J. M. STAGG (General PERRIER, who proposed, pointed out that most of the funds in hand were banked in England, that it would be long before money could pass easily from country to country, and that the General Secretary should, for the time being, be English. Dr. J. A. FLEMING seconded and the proposal was then carried unanimously).

It was agreed that these appointments should be taken up at once in the case of the President, and as soon as he was made available from war duties in the case of the General Secretary.

In subsequent discussion the danger of unanticipated casualties was brought up, and the following resolution was proposed, seconded, and carried:

Resolution 1: That the General Secretary of the Union should be invited to propose for appointment by the Executive Committee a deputy who would act for him in case of incapacity; and that the desirability of such a step being taken in the Associations should be brought to their notice.

Next General Assembly--Whilst many have asked for a General Assembly at the earliest possible moment, it is becoming increasingly obvious that facilities for travel, and the necessary supplies, are unlikely to allow of the congregation of several hundred delegates in 1946. The President, speaking for Norway, repeated the invitation made to the Union in 1939 to hold the next General Assembly there, but said that he thought we should agree on 1947.

As, however, it was obvious that many administrative questions would have to be solved, and that an Extraordinary General Assembly, limiting the attendance to one (or, if a minority opinion were in question, two) delegates from each country, could be convened to deal with them, he advocated calling such a meeting in 1946. This Extraordinary General Assembly (Statute 11) would insure that the subsequent Ordinary General Assembly, the eighth in the sequence, was untroubled by administrative matters, and free for its proper scientific mission. The following resolutions were passed:

Resolution 2: That the next (eighth) Ordinary General Assembly shall be held in Norway in 1947.

Resolution 3: That all administrative questions which face the resumption of Union activities be decided by an Extraordinary General Assembly in 1946.

The General Secretary pointed out that it was doubtful whether all such questions could be sufficiently studied, and defined, soon enough to give adhering nations the four months' notice called for in By-Law 9. He promised to do his best, and the meeting was agreed that at the present time this By-Law must not be allowed to interfere.

The opinion was general that the Extraordinary General Assembly should be held in England, as most central, and it was left to the General Secretary to decide upon actual time (late July was suggested) and place.

Reopening subscription--The collection of subscriptions became impossible during the autumn of 1940. Since that time some countries had continued, even when overrun, to put aside funds for the Union and to keep alive such Associations as were centered in occupied countries, but whose reserve funds were banked in England. The Committee, heard, with warm commendation, of the action taken in such cases.

It was then resolved that:

Resolution 4: Regular subscription shall be resumed as from the beginning of 1946.

Resolution 5: Since the finance of the Union is centered in England the Unit of Subscription for 1946 shall be £100.

In connection with Resolution 5 it was pointed out that, before the war, the actual gold-franc unit was equivalent to £99, and that £100 today was worth far less.

At the present time it is too early to decide upon either the amount of income which the Union will require (and therefore the future size of unit), or the currency in which it is to be paid. These matters will, no doubt, be discussed at the forthcoming Extraordinary General Assembly, although, even then, wage levels and rates of exchange can hardly have become stable.

General Secretary's report--The financial paragraphs of the General Secretary's report were considered next, since they bear on the subject of a reopened subscription. After hearing how involved any strict accounting between the nations would be, and how little there was to gain by it, the Committee resolved:

Resolution 6: Friendly countries, involved in the war, shall be asked to subscribe as from 1946, no notice being taken of war years.

Resolution 7: Adhering countries, which were not involved in the war, and which had not paid for 1940 and/or for 1939, shall be asked to pay one year's subscription in virtue of such debts, before subscribing for 1946.

In the General Secretary's report it is stated that the printed reports of the Washington General Assembly had been distributed to certain countries, but not to others, whilst the Resolutions passed at Washington had not yet been sent to the countries interested.

Resolution 8: The Resolutions passed by the Washington General Assembly shall be reprinted as a separate pamphlet, and sent to the countries interested.

Associations were asked to forward, to the General Secretary, lists of countries interested in the Resolutions for which they were responsible.

The financial position of the Union was discussed and the balance sheet (January 1, 1939, to November 30, 1945) was examined. This balance sheet did not, however, include the sub-account held in the U. S. A., nor any details of the payments to Associations made by countries during German occupation. The President explained what had been done in Denmark, Holland, Sweden, Finland, and Norway, whilst General PERRIER reported on what had been done in France. In view of Resolutions 6 and 7 no further action was recommended in these cases. As the resources of the Union seemed to allow of a return to the normal it was resolved that:

Resolution 9: The normal distribution of Union funds to Associations shall be carried out in 1946, beginning, if possible, in May.

In discussion upon the foregoing report it was pointed out that the Union had directly financed certain undertakings (for example, the Seismological Summary), and had met certain debts for Associations which were unable to draw upon their British-banked accounts.

On the other hand certain Associations in occupied countries have received funds of which the Union has no cognizance.

A strict accounting of such emergency measures was felt to be both invidious and unnecessary and it was resolved:

Resolution 10: In making distribution of Union funds to the Associations, no notice shall be taken of any emergency receipts or payments during the war.

In view of Resolution 3, however, and of By-Law 17, complete accounts, up to the end of 1945, for Union and Associations alike, must be printed and sent to adhering nations as early as possible before the Extraordinary General Assembly in 1946.

Policy--All present at the meeting had heard talk of bodies, representing the United Nations, whose terms of reference included education, science and more vaguely, culture. United Nations Educational, Scientific, and Cultural Organization (UNESCO) is the portmanteau title of the body most frequently mentioned. The Union itself has not been approached by any such body, but the International Council of Scientific Unions (ICSU) has been, and is, in touch with UNESCO.

At the meeting of the Executive Committee of the ICSU, a meeting which preceded our own by a few days, our two representatives[2] were Professor PROUDMAN and Mr. W. D. LAMBERT. These two gentlemen reported on what had been discussed but were not able to give definite details about the future of UNESCO. Further discussion seemed useless, although it is quite certain that a body with so large a mandate must affect us.

The Committee welcomes the advent of any body whose efforts may tend to a fuller scientific cooperation between the nations of the Earth. It considers, however, that administration and finance cannot be divorced from scientific leadership, and that the Scientific Unions should have a common policy, and speak with a common voice in these matters. The International Council of Scientific Unions is the natural head and spokesman of the Unions which adhere to it.

The policy of the Scientific Unions as a whole, as well as that of this particular Union, is mentioned in an important list of Recommendations from the British National Committee for Geodesy and Geophysics. The Executive Committee discussed some of these Recommendations, leaving others to come before the Extraordinary General Assembly of 1946. The Committee resolved:

Resolution 11: That services of a permanent or quasi-permanent nature should be financed and inspected as recommended by the British National Committee in paragraphs 4, 5, and 6 of its Recommendations.

Non-adhering and/or ex-enemy countries--The importance of making the activity of the Union as world-wide as possible was stressed at almost every session of the meeting. Naturally the first step, so obvious as to call for no formal resolution, is to get in touch with countries which have adhered in the past, but have left by reason of the hardship of the population basis of subscription (for example, India), or because of internal affairs (for example, Spain). Thereafter comes a list of countries, such as Turkey, China, Persia, etc., whose cooperation would be of great value, but which have not, so far, adhered. As regards ex-enemy countries it was resolved that:

Resolution 12: Ex-enemy countries should be approached with a view to their adherence as and when their governments are recognized by the United Nations.

The form of Agreement under which countries may adhere--When the Scientific Unions were formed, the Agreement, upon which adherence was based, was between private bodies, such as Academies of Science characteristic mainly of Europe and North America. Later in our development many adhering nations have asked for a diplomatic, rather than a private, Agreement. Discussion, in the Committee, ranged over a variety of possibilities, namely: (a) Entirely diplomatic, with the proviso that the nomination of delegates and the expression of opinion on scientific matters shall be left to the unfettered discretion of the relevant scientific bodies; (b) entirely as between Academies of Science or other scientific bodies; and (c) either the one (a), or the other (b), at the discretion of the country in question.

In the discussion which followed, and in the following report, the word "Convention" is used solely to define that text of the Statutes which is to obtain for 12 years from the date of signing. It is moreover understood that an Agreement of form would be one between the Foreign Office of the country of which the that-time General Secretary was a national on the one hand, and the Foreign Offices of the remaining adhering countries on the other.

It was also understood that the form of Agreement [either (a) or (b)] should consist of principles stated as concisely as possible, whilst routine measures for acting upon those principles should be embodied in By-Laws for which General Assemblies would assume responsibility.

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[2] Dr. J. A. FLEMING of IUGG also attended as a regularly elected member of the Executive Committee of ICSU.

General PERRIER spoke strongly in favor of a Diplomatic Agreement, instancing the successful working of the old Geodetic Association (Potsdam), and the Bureau des Poids et Mésures (Paris). The majority, indeed, favored a Diplomatic Agreement, but it was decided that the final decision must rest with the Extraordinary General Assembly of 1946, and finally resolved that:

Resolution 13: The General Secretary shall provide a model of Agreement for (a) or (b), and shall investigate whether, in fact, a compromise on (c) is possible. This information to be sent to adhering nations four months before the Extraordinary General Assembly.

The General Secretary refused to commit himself but promised to do his best.

Basis of subscription--Population or free choice of class--A review of the working of the population-basis as specified in the Statutes has shown that basis to have serious defects. It was proposed that in the revised Statutes subscriptions should follow a free-will basis, by which is meant that each country should be free to choose a definite number of subscription-units as its annual contribution. The Executive Committee of the Union should have power to refuse membership to any country which offered a contribution obviously much too small. In the first place maximum and minimum limits for a unit-subscription would be fixed. The actual value of the unit-subscription would be settled from time to time according to the total annual budget and the total number of units subscribed by the adhering countries.

General PERRIER proposed the basis followed by the International Bureau of Weights and Measures. This method is based on the smaller states each contributing 0.005 of the estimated annual budget and the larger states 0.15; any balance necessary is proportioned according to populations. If such were adopted by the Union serious modification would be necessary in special cases.

After discussion the question of choice between these two systems was put to a vote of all persons present; the vote showed a decided majority in favor of recommending to the next General Assembly the free-will system for a trial-period.

Resolution 14: The free-will type of subscription should be given a trial-period, and the Extraordinary General Assembly is, hereby, asked to inaugurate that trial.

It was agreed that clear, concise descriptions of both methods be circulated to the various National Committees as soon as possible for consideration and instruction of delegates to the Extraordinary General Assembly of 1946.

Resolution 15: The free-will system whilst entirely divorced from population shall include the number of categories (8), and the system of voting, as defined by Statutes 12 and 15.

The Statutes--Much discussion followed upon the wording and arrangement of the Statutes. It was generally agreed that the Union had had so much bother in the past because we had never devoted enough time to putting them into efficient shape in the first instance. It was agreed that we wanted a clear and brief definition of principles, unencumbered by procedure, as the original agreement, and that is already covered by Resolution 13.

The rules of procedure should be laid down in By-Laws subject to such changes as a majority vote during any General Assembly should demand.

Resolution 16: The General Secretary shall provide a model of By-Laws to accompany the form of Agreement envisaged by Resolution 13.

The text of the Statutes drawn up by the late President of the Union was discussed, and discarded as failing to clear principle from procedure, and as keeping to the population-basis of subscription, which, in practice, was but camouflage for an extensive list of exceptions.

The Associations--Towards the close of the meeting Presidents or Secretaries gave brief résumés of the war-time activities of their Associations. One or two matters of general import emerged.

In the first place it is important that Associations should replace casualties in their Executive Committees, in order that steps may be taken to frame suitable programs for the General Assembly of 1947. Then it has happened in certain cases that bank accounts have been held in one name only. War casualties have shown the danger of that practice. Every bank balance should be under at least two names. Thirdly there should always be a deputy available for the General Secretary of an Association just as has already been recommended in the case of the Union. Secretaries are, if anything, harder to replace at short notice than Presidents.

Other business--(1) A cordial, and welcome, invitation from the Pan-American Institute asks the Union to be represented at its cartographic meeting in Caracas during the forthcoming year. The invitation is to be accepted and acted upon.

(2) The advantages of a proper publicity were discussed on several occasions. The inclusion of popular lectures at each General Assembly--begun at Edinburgh in 1936--is an instance of useful publicity. The lack of a brief and clear booklet on the social value of Earth Sciences has long been felt. On the other hand easy and wordy overstatement may do more harm than good. With these points in mind the Committee resolved:

Resolution 17: A Committee on the Social Value of the Earth Sciences shall be formed, with the object of preparing a general statement on the value of the Earth Sciences for human welfare, and of instituting such other forms of publicity as may, from time to time, be desirable.

Several names were mentioned, amongst them the following: Professor C. F. BAESCHLIN, Professor SYDNEY CHAPMAN, Dr. JEAN COULOMB, Dr. RICHARD M. FIELD, Sir GERALD LENOX-CONYNGHAM, Dr. N. E. NÖRLUND, Dr. HANS PETTERSSON, M. JEAN ROTHÉ, and Dr. PEDRO C. SÁNCHEZ. Other names may present themselves shortly,[3] and there would be power to co-opt. The Committee, when formed, would choose its own Chairman.

(3) The thanks of the Committee were due to Christ Church and Hertford Colleges for board and lodging, to the School of Geography, for a meeting room, and to a certain defense establishment for the hospitality of its canteen. Resolutions of thanks to each of the above four were passed, and were subsequently sent to the appropriate addresses.

The close of the meeting--Business was completed by lunch on December 14, and the President dismissed the meeting with the following words:

"Gentlemen: We are now at the end of our meeting. I think it has been a valuable one, and I hope it will prove useful to the Union we serve with our sincere interest. We may recapitulate some of the results:

"We have decided to invite nearly all previous members to re-open subscription at once, and to induce another series of countries to become new members of our Union, thus not only endeavoring to knit together the pre-war threads of cooperation, but to extend our activities to an even wider circle than hitherto. It is to be hoped that thereby our Union will be enabled to carry out successfully its share in the general work of conciliation amongst the nations. We have had to take account of the peculiar situation caused by the war. We have decided to call our members not to one, but to two General Assemblies, both of them to take place at the earliest dates possible. We propose to divide the Agenda into two parts--administrative and scientific. It may be hoped that, thus, we shall attain a maximum of efficiency. We have started the compilation of Statutes better framed and arranged than those now existing, utilizing our experience from former years. We have come to unanimous recommendations of altered principles with regard to the old, and very much discussed problem of the basis of subscriptions, and we have taken important steps in financial matters. We have reached these and other conclusions in an atmosphere of good comradeship and been happy in having had the opportunity of a moderate concentration in peaceful and otherwise charming surroundings.

"From this chair, on behalf of the Union, I thank all of you for what has been attained here in Oxford. I am sure nobody will oppose to my paying special homage to two persons, namely, our outgoing but happily still acting General Secretary, and our friend Colonel LACLAVÈRE. Adjectives are superfluous. With best wishes for all of you and our Union, I declare our meeting ended."

[Note: The forms of Convention and By-Laws (or rules of Procedure) as prepared by General Secretary WINTERBOTHAM are published in full in the Journal of Terrestrial Magnetism and Atmospheric Electricity, v. 51, pp. 112-118, 1946--Ed.]

River Cottage, Sutton Courtenay,
Berkshire, England, January 26, 1946

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[3] Professor G. CASSINIS, Mr. NOEL J. OGILVIE, Professor W. T. THOM, Jr., Dr. THOMAS G. THOMPSON, and Dr. F. A. VENING MEINESZ were later added and Dr. RICHARD M. FIELD was made Chairman.--Ed.

Transactions, American Geophysical Union Volume 27, Number II April 1946

REPORT OF THE CHAIRMAN OF THE SPECIAL COMMITTEE ON UNITS

H. H. Howe, Chairman

This report has been prepared by the Chairman of the Committee, to inform Members of the Section of Terrestrial Magnetism and Electricity of the activities of the Committee to date. It is not to be construed as a report of the Committee.

The Special Committee on Units was authorized by the Section in 1941 [see MINUTES, "References" at end of Report]. Through oversight, it was not appointed at that time, and it was again authorized in 1942. It was actually appointed early in 1943, and hence has been in existence about three years. The Members of the Committee are H. H. HOWE (Chairman), F. C. FARNHAM, H. T. STETSON, E. H. VESTINE, and FRANK WENNER.

The Committee has led a rather desultory existence, and, as shown by the minutes for 1943, 1944, and 1945, there has been discussion in the Section over whether it should be continued. The argument centered on two points: Whether such a Committee could be expected to accomplish anything, and whether the actual product of the Committee justified its continuance. It is admitted that the Committee has, in fact, deliberated (by mail) only during the few months preceding each Annual Meeting, and has been inactive during the remainder of each year. One reason contributing to these periods of inactivity is that this Committee has been, so far as the Chairman is concerned, a strictly "extra-curricular activity," whereas the members of some committees of the Union have been authorized to do their committee work during their office hours.

The deliberations of the Committee cover 34 pages, most of them processed by hectograph. A few extra copies of these pages are available for distribution to interested Members of the Section. Three different questions have been discussed; of these, the first two have been debated before the Section, proposition A in 1943, and B in both 1943 and 1944. It is believed that the Section approved the Committee's recommendation on B in 1944, but the resolution fell afoul of parliamentary confusion to such an extent that its status is somewhat in doubt.

In 1945, it was decided not to present any resolutions. It is hoped, however, that the meeting in 1946 will take some definite action upon all three of these subjects, and it is for that reason that this report is being published in the Transactions. The three subjects which have been considered by the Committee are outlined below.

Proposition A--Unit of resistivity

This subject was proposed to the Committee by F. C. FARNHAM. (Note, however, that it was proposed to the International Union of Geodesy and Geophysics in 1939 [MERCANTON, 1940].) There is a widespread use of units that are dimensionally incorrect, namely, "ohms per cubic meter" and "ohms per cubic centimeter." Therefore, the Committee condemned these units. In addition, however, it made recommendation as to which of the many correct units ought to be used.

The actual resolution at one time approved by the Committee appears in the minutes of 1943. An amplified version of it, prepared by the Chairman and including some portions not yet approved by the Committee, is given below. It has been divided into two parts, the first condemning the incorrect usage and the second expressing a preference among correct usages.

"(1) The Section of Terrestrial Magnetism and Electricity of the American Geophysical Union urges that the units used in giving the results of geophysical measurements be dimensionally correct. For example, 'ohms per cubic meter' and 'ohms per cubic centimeter' are impossible units of volume-resistivity, and such terms should be avoided. Similarly, 'ohms per square centimeter' or 'ohms per square kilometer' is an incorrect unit for the resistivity of the air between the Earth and the ionosphere. Dimensionally correct units are, respectively, 'ohm-meter,' 'ohm-centimeter,' 'ohm-centimeter-squared,' and 'ohm-kilometer-squared.'

"(2) For the unit of volume-resistivity of the Earth, the ohm-meter is preferable to the ohm-centimeter for two reasons: (a) It is of more convenient size; (b) it is the basic unit of resistivity in the mks system, whereas neither one is the basic unit in the cgs system. However, 'ohm-meter' might be mistaken for the name of an instrument, especially in oral discussion; therefore, we recommend that the unit of Earth-resistivity be called the 'meter-ohm,' written with a hyphen."

Proposition B--Magnetic field-intensity

This subject was presented to the Committee by H. H. HOWE. It was to consider this subject that the Committee was originally proposed, following a suggestion made by N. H. HECK, then Chief of the Division of Terrestrial Magnetism and Seismology of the United States Coast and Geodetic Survey (now retired).

The Chairman is satisfied with the following resolution, reprinted below, from the minutes of 1944:

"The Committee urges that the Section recommend that geophysicists follow the practice, already adopted by international action of certain other scientists, of using 'gauss' as the unit of flux-density and 'oersted' at the unit of magnetic field-intensity. It is, however, recognized that the flux-density in gauss is numerically equal to the intensity in oersteds, within practical limits of measurement, for measurements in air. Therefore, it is not necessary that geophysicists in general take into account which quantity their instruments measure, since when one is measured the other is known. However, in giving results, either the intensity should be stated in oersteds or the flux-density should be stated in gauss; expressions such as 'the vertical intensity was 0.555 gauss' should be avoided, as being contrary to international action."

This was tentatively approved by the Section in 1944, and the Committee on Resolutions was supposed to draw up a resolution for submission to the Union. That Committee, however, added considerable material that had not been acted upon by this Committee, including most of that in reference [WENNER, 1944]. This is the "resolution on nomenclature" mentioned in the minutes of 1944, which was tabled.

It is the feeling of the Chairman of the Committee that while this material [WENNER, 1944], with certain revisions, would be suitable to accompany a resolution on the subject, the resolution itself should be short, not much longer than the one given above.

Proposition C--English versus metric system

This subject was proposed by H. H. HOWE in 1943. There was substantial agreement among the Committee upon the desirability of using the metric system, but no specific resolution was agreed upon. As a basis for discussion, the following resolution proposed by HOWE is given here.

"The American Geophysical Union urges that all organizations, either public or private, which make maps or geophysical surveys, use the metric system whenever it can be done without substantial inconvenience to the organization or to the public. At present, many organizations use the customary units in describing stations or making maps, and use equivalent metric units only as a grudging concession when it seems necessary to do so. It is urged that this attitude be reversed; thus, if it is possible to do so, all original measurements should be made in metric units, excepting surveys in which they are made in both units as a check (some examples of measurements which cannot be made in metric units are measurements of distance by speedometer or by Land Office section lines); office reductions should be in metric units; and published results should be in metric units, the customary equivalents being given parenthetically if substantial inconvenience to the expected user would result from the use of metric units exclusively.

"All kinds of activities would be greatly facilitated if the metric system were generally used. It is already in general use throughout much of the world, including many so-called backward countries. Millions of Americans have spent part of the last four years in countries in which the metric system is in general use, and so are somewhat familiar with it. Therefore, this would be an opportune time for more general use of the metric system in this country.. It is the proper function of scientists, who have already learned the advantages of the metric system in the limited field of scientific measurements, to promote its general use."

In addition to seeking the opinions of the Committee on this resolution, the Chairman wrote to LYMAN BRIGGS, who was then Director of the National Bureau of Standards. His reply, in part, was as follows:

"It is the policy of the National Bureau of Standards neither to advocate nor to oppose the increased or exclusive use of the metric system in this country, but rather to direct its efforts toward increasing the accuracy and convenience of use of whatever system of units of measurement is found by science, industry, commerce, to be best suited to their respective needs.

"On the other hand, I have expressed myself on many occasions as fully appreciating the advantages of the metric system as applied to science and to certain branches of engineering. Believing as I do that the general adoption of the metric system should come, if it comes, as a result of education and of a real desire of the people to have it, instead of being by any government mandate, it seems that the first paragraph of your resolution is a particularly fitting one for your Committee to propose.

"In your second paragraph, the first sentence undoubtedly expresses the sincere belief of the author. But it seems to me that it is entirely too broad. For the vast majority in this country the adoption and general use of the metric system would result in little, if any, advantage, while the change would be accompanied by no little inconvenience and expense. Many influential men in business realize this and are strongly adverse to the adoption of the metric system. I believe that your resolution would command a more widespread respect if that first sentence of the second paragraph were more moderate and read: 'A great many other kinds of activities would be much facilitated if the metric system were more generally used.'

"I have no objection to your quoting from this letter in your Committee report."

The Chairman is inclined to disagree with the statement that the metric system would be of little if any advantage to the vast majority of the people of the country. For example, he was recently called in as an expert to help determine whether a certain group of venetian blinds would fit into another house. What with differences of opinion as to whether measurements should be in inches or in feet and inches, the difficulty of ready multiplication by 12, and the use of one 36-inch measure and one 60-inch measure, the problem became quite complicated by comparison with what it would have been in meters and centimeters.

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U. S. Coast and Geodetic Survey,
Washington 25, D. C.

Transactions, American Geophysical Union Volume 27, Number II April 1946

NOTES ON ACTIVITY OF PARÍCUTIN VOLCANO DURING JANUARY, 1946

Konrad B. Krauskopf

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The fairly strong eruptive activity at the end of December died out abruptly on January 2. There followed a quiet period reminiscent of the three weeks between November 16 and December 7, with a very thin column of light gray dust and only feeble noise from the crater. Between January 19 and 21 activity gradually increased, producing more noise, a denser column, and small showers of incandescent rocks. On the 27th the cloud became dark gray, much denser and wider, and the noise changed to loud muffled explosions. The dense cloud persisted with minor interruptions to the end of the month; the noise was very loud at intervals, but practically absent at other times; showers of incandescent rocks were more numerous and more impressive than any time in the past three months. The dark cloud of these last few days produced the only considerable sand falls since last October.

The bocas and the lava flows showed their usual complete independence of the activity of the crater. On January 10 the east-west boca ridge, dormant for a month, suddenly renewed activity with a bubbling lava pool and some small new flows. After a day or two activity subsided again, then burst out once more on January 21. The lava pool itself remained violently active only for two days and then crusted over, but a new lava flow was established which was still moving rapidly at the end of the month. The birth of this new flow seemed to sap the strength of the flow moving out of the north-south boca ridge; the flow quickly declined to a very small and sluggish one, and even emission of vapor from the north-south ridge practically ceased. The sudden transfer of lava activity from one boca ridge to the other probably means no significant change in the total amount of lava coming from the ground.

The long flow from the north-south ridge, now one of the major Parícutin flows, continued to move up to the end of the month, but the drying up of its source of supply when the east-west ridge renewed activity caused the flow to decline rapidly in the period January 21-31. During the month the flow continued to move down the broad valley northwest of Parícutin, sometimes spreading out into a broad lobe and sometimes moving as a tongue only a few hundred meters wide. Its tip is now farther west than any other Parícutin lava. The new flow from the east-west ridge is moving down the valley between the old No. 1 and No. 2 flows and has already reached the base of the steep slope west of the casita--about 1.5 kilometers from its source.

The form of the crater has gone through a cycle similar to that of November and December; namely, the development of an elaborate pattern of fissures and faults roughly concentric around the inner crater, apparently representing slumping toward the interior, and then the disappearance of the pattern as eruptive activity became more violent. Slumping this time was more pronounced than in December, extending even beyond the south rim of the crater.

[W. D. Johnston, Jr., recently appointed Geologist in Charge of the Section of Foreign Geology of the United States Geological Survey, visited Parícutin Volcano March 7, two days after the recent outburst. He indicated that the outburst was spectacular, having showered glowing bombs over the entire cone about 8 o'clock one evening, but lasted only two or three days, from the 3rd to about the 5th. Carl Fries, Jr., of the Geological Survey visited the Volcano a few days after the eruption, and for the first time was able to photograph the vent itself. He said that the cone was less active than during any of his previous visits.--Ed.]

U. S. Geological Survey,
Washington, D. C.

(Communicated manuscript received March 12, 1946)

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REPORT OF COMMITTEE ON GLACIERS, 1945

François E. Matthes, Chairman

(Published with the approval of the Director of the United States Geological Survey)

The membership of the Committee has remained unchanged during the past year. It is as follows: WILLIAM H. HOBBS, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan; LAWRENCE MARTIN, Chief, Division of Maps, Library of Congress, Washington, D.C.; JAMES E. CHURCH, President, International Commission of Snow and Glaciers, Agricultural Experiment Station, University of Nevada, Reno, Nevada; WILLIAM OSGOOD FIELD, Jr., home address, 18 West Twelfth Street, New York City; OLIVER KEHRLEIN, Chairman, Committee on Glacier Studies, Sierra Club, 1050 Mills Tower, San Francisco, California; KENNETH N. PHILLIPS, Hydraulic Engineer, Water Resources Branch, Geological Survey, and Chairman, Research Committee of the Mazamas, Post Office Building, Portland, Oregon; WILLIAM S. COOPER, Professor of Botany, University of Minnesota, Minneapolis, Minnesota; GERALD FITZGERALD, Chief of the Aeronautical Chart Service, Army Air Forces, Washington, D. C.; LAURENCE M. GOULD, President of Carleton College and Professor of Geology, Northfield, Minnesota; ARTHUR JOHNSON, Hydraulic Engineer, Conservation Branch, Geological Survey, Washington Building, Tacoma, Washington; WELDON F. HEALD, 3126 Rubio Canyon Road, Altadena, California; HOWARD R. STAGNER, Park Naturalist, Mount Rainier National Park, Longmire, Washington; and FRANÇOIS E. MATTHES (Chairman), Senior Geologist, Geological Survey, and Secretary, International Commission of Snow and Glaciers, Geological Survey, Washington 25, D. C.

Variations of Glaciers of the United States, Reported in 1944

Glaciers of Mount Olympus, Washington

To PRESTON P. MACY, Superintendent of Olympic National Park, the Committee is indebted for the first data on the recession of the Blue Glacier, one of the major ice streams on Mount Olympus. Annual measurements to its terminus were begun in 1938, the year in which Olympic National Park was established, and such measurements, MACY states, will be continued in future years, circumstances permitting. Thus one more sizable glacier is added to the list of ice bodies in the western United States whose variations in length and volume in response to current climatic fluctuations are being observed from year to year.

The special value to science which these data on the behavior of the Blue Glacier will have resides in the fact that this glacier is representative of the larger ice streams on the Olympic Peninsula, which is reputedly the wettest corner of the continental United States. Rainfall at the lower levels averages from 140 to 150 inches per year. Data on snowfall at the higher levels are as yet meager, but it can hardly be doubted that snowfall there is very heavy also, as a result of the abrupt orographic lifting of the moisture-laden, polar-maritime air masses that approach from the southwest and the west, especially during the winter months.

The effects of these climatic conditions are reflected in the extraordinary abundance of ice bodies in the Olympic Peninsula and in the relatively low altitudes at which they originate. The topographic map of the Mount Olympus quadrangle, prepared by the Corps of Engineers of the United States Army, shows that within its boundaries alone there exist more than 100 glaciers, large and small, the aggregate area of ice being not less than 25 square miles. More precise figures than these can not be given, as no distinction is made on the map between seasonal snow accumulations and perennial ice bodies. The map was constructed with the aid of stereoscopic plotting instruments from aerial photographs, and as those photographs evidently were taken at a time of the year when many temporary snowfields and remnants of snow avalanches had not yet melted away, it shows a bewildering profusion of white patches among which some of the lesser glaciers can not be identified with certainty.

The Olympic Mountains have no great height. Mount Olympus, the culminating summit, attains an altitude of 7,954 feet; many of its satellite peaks are less than 7,000 feet high; and the neighboring mountain crests range in altitude between only 5,000 and 6,000 feet. The central Olympus massif, accordingly, rises but little above the level of the base of Mount Rainier, yet the massif bears more than ten square miles of glacier ice. The loftiest névés head at altitudes of about 7,800 feet, but the main gathering basins of the larger ice streams lie at altitudes between 6,000 and 7,000 feet--that is, at a level corresponding roughly with that of the timber-line in the Mount Rainier region. Of the cirque glaciers in the vicinity of Mount Olympus, the majority originate at altitudes between 5,500 and 6,500 feet; some lie on the northerly slopes of mountain crests scarcely over 5,000 feet in height.

The regional snow line on the Olympus massif is difficult to determine with accuracy, because of the exceeding irregularity of the topography, but from a study of the larger névé bodies shown in photographs, it may be inferred that the line lies between 6,500 and 7,000 feet. This is without doubt the lowest level to which the regional snow line descends within the continental United States. (The regional snow line, as defined in the report of this Committee for 1942, Trans. Amer. Geophys. Union, Part II, p. 379, 1942, marks the lower limit of the zone in which snow accumulates to sufficient depth to form glacier-ice on all surfaces of the land, except those from which the snow is shed in avalanches and those from which the snow is swept by the wind.)

A comparison with Mount Baker is instructive. Mount Baker stands only 30 miles from the eastern shore of Puget Sound, but fully 140 miles from the outer Pacific Coast, and it therefore receives less precipitation than Mount Olympus, which stands only 40 miles from the open seaboard. According to HERBERT W. GLEASON [see "References" at end of paper, 1907], the timber-line on the north side of Mount Baker lies at an altitude of about 6,000 feet. On that mountain, therefore, the regional snow line is presumably at altitudes between 7,500 and 8,000 feet. On Mount Rainier, it rises to altitudes little short of 9,000 feet.

Inasmuch as the glaciers of Mount Olympus are still so little known, it may be appropriate here to indicate the dimensions of the six largest, and to stress the fact that four of them attain lengths of three miles or more. Those glaciers therefore are comparable in magnitude to the average, but not the largest, of the ice streams in the European Alps. The dimensions in Table 1, it should be noted, are those which the glaciers had in 1933, the year in which the aerial photographs for the topographic map were taken.

Table 1--Data on glaciers in the Mount Olympus region

Name	Length in 1933	Area in 1933	Altitude of upper névés	Altitude of terminus	Direction of movement
	mi	sq mi	ft	ft	
Hoh	3.8	2.6	7,800	3,400	NE
Blue	3.2	2.7	7,800	3,800	NE and N
White	2.7	2.1	6,800	3,700	N and NE
Hubert	2.7	1.5	7,300	3,600	S and SW
Jeffers	1.8	0.7	5,900	3,400	NE and SE
Humes	1.6	0.8	6,300	4,500	E

In 1933, it will be seen, the Blue Glacier stood a close second in point of length and first in point of areal extent. However, as all of these ice streams have shrunk considerably in size since 1933, and probably at somewhat different rates, their present order may differ from that in which they appear in the table. The recession record of the Blue Glacier during the past six years is shown in Table 2.

Table 2--Record of recession of Blue Glacier

Dates of measurements to terminus of Blue Glacier	Recession
	ft
August 30, 1938, to September 1, 1939	27.6
September 1, 1939, to September 5, 1940	83.0
September 5, 1940, to October 28, 1941	185.5
October 28, 1941, to October 5, 1943 (2 years)	139.0
October 5, 1943, to September 26, 1944	78.0
Total recession, 1938-1944	513.1
Mean rate of recession per year	85.5

Regarding the reduction in length which the Blue Glacier may have suffered since 1933, some conception may be obtained from a comparison of its rate of recession during the past six years with that of the Nisqually Glacier on Mount Rainier. From 1938 to 1944 the Nisqually receded a total distance of 494 feet, the mean rate being 82.3 feet per year. During those six years, therefore, the Blue Glacier and the Nisqually receded at nearly the same rate. This close parallelism between their behavior, it is realized, may be only a coincidence, as the local conditions in the two cases differ widely. The Blue Glacier has a winding northerly course and a slender, tongue-shaped terminus encased in a narrow gorge, whereas the Nisqually descends in a southerly direction and terminates in a broad ice cliff exposed to the rays of the mid-day Sun. Nevertheless, it may reasonably be supposed that the two glaciers behaved essentially alike prior to 1938 as well as since, and the recessional history of the Blue Glacier, therefore, in the absence of further data, may be patterned after that of the Nisqually all the way back to 1933. During the whole period from 1933 to 1944 the Nisqually receded at a mean rate of 83 feet per year and was shortened a total of 913 feet. Assuming, then, that the Blue Glacier receded at a mean rate of 85.5 feet throughout the same period, it would have been shortened 940 feet. Its present length, accordingly, is presumably 3.2 miles less 940 feet, or 3.02 miles.

The other five ice streams on Mount Olympus doubtless have been reduced in length on a roughly comparable scale. The Hoh, White, Hubert, and Jeffers, all of which, like the Blue, reached down to elevations around 3,500 feet in 1933, now are presumably about 900 feet shorter than they were in that year; but the Humes Glacier probably has been shortened much less, for in 1933 it ended at an altitude of 4,500 feet--1,000 feet higher than the other glaciers.

It is entirely possible, as MACY suggests, that the rapid recession of the Blue Glacier during the past six years has been due to the slenderness of its terminal ice tongue. That ice tongue now has practically ceased to exist, and MACY therefore anticipates that henceforth recession will proceed at a slower pace because of the greater breadth of ice that will be exposed. If that proves to be true, then the foregoing estimates of the shortening of the other five glaciers on Mount Olympus, as based upon the recession of the ice tongue of the Blue Glacier, may be too large. It is to be hoped that opportunity will be found in future years to make annual measurements also to one or more of the other glaciers.

Of special interest among the photographs of the Blue Glacier which MACY has supplied is one that is said to have been taken by a Mr. WATTERS "about 25 years ago." It portrays the glacier as it appeared around 1919, when its dimensions truly dwarfed those of the present time. In order to give an adequate conception of the change in the size of the glacier that has taken place since 1919, it should be explained that the main body of the Blue Glacier occupies a gently sloping "hanging valley" that ends abruptly at a height of 1,500 or 1,600 feet above the floor of the great U-shaped trough through which Glacier Creek flows northward to the Hoh River. The slender ice tongue to which MACY made his measurements hung steeply from the lip of that hanging valley. In 1933, according to the topographic map, it reached about halfway down to the floor of the U-trough. WATTERS' photograph, in contrast, shows the Blue Glacier descending in the form of a massive ice-cascade all the way down into the U-trough. It also shows that in 1919 large chunks of ice broke off periodically from both margins of the glacier at the lip of the hanging valley and fell in avalanches over the cliffs. Below, the avalanched masses were in part reunited with the main ice stream, thereby increasing its bulk in the U-trough. How far down the U-trough the rebuilt glacier extended can not be determined from the photograph, but the ice masses that are in view suggest that it attained a length of perhaps 1/4 mile. If that estimate is correct, the Blue Glacier may have been shortened as much as 3/4 mile since 1919.

Again, comparison with the Nisqually's recession record seems enlightening. As is known from actual measurements made by the National Park Service, from 1919 to 1944 that glacier receded a total distance of 1,864 feet. The Blue Glacier, then, would appear to have receded more than twice that distance during the same period. This seems an unexpectedly large disparity, considering that the two glaciers have been receding at nearly the same rate during the last six years. It is possible, however, that the ice cascade of the Blue Glacier, being composed of clean ice, and cut by many crevasses, wasted away much faster than the compact and debris-mantled body of the Nisqually Glacier. In any event, the WATTERS' photograph affords indubitable testimony, as far as it goes. There is, nevertheless, a possibility that it is not correctly dated. It is said to be "about 25 years old," but it may be much older. On that point further information is needed, and it is to be hoped that its date eventually will be established definitely. Search for other dated photographs would be extremely worth while also; by means of a series of such photographs the recessional history of the Blue Glacier might possibly be traced back over several decades, and a valuable insight would be gained into the behavior of the Olympic glaciers in general during that period.

Glaciers of Mount Rainier, Washington

Nisqually Glacier--ARTHUR JOHNSON, Hydraulic Engineer of the Geological Survey, reports that the three profile-lines across the lower part of the Nisqually Glacier which have been resurveyed annually for several years past, for the purpose of determining the rate at which the surface of the ice is being lowered by ablation, were surveyed once more in 1944. These annual resurveys are made usually in the last week of August, the endeavor being to space them 12 months apart as nearly as practicable, but in 1944 owing to unfavorable weather the resurvey had to be deferred to the latter part of September. The changes reported in 1944, therefore, represent the results of 13 months of ablation instead of 12 months. This fact is to be borne in mind when the figures for 1944 are compared with those of previous years.

The figures for 1944 are indeed appreciably larger than those for 1943 and 1942; nevertheless, there is reason to believe that the increase is due not entirely to the additional month, but in part also to the fact that precipitation during the winter of 1943-44 was unusually low. As JOHNSON points out, precipitation during that period was far below normal throughout the Pacific Northwest. At Tacoma the total amounted to 26.22 inches, as compared with a mean of 40.40 inches; and at The Dalles, Oregon, the runoff from the Columbia River basin was only 61 per cent of normal--the second lowest recorded since 1878. No data on the snowfall in the Mount Rainier region are at hand, but it may reasonably be presumed that it also was below normal and that, as a consequence, the snow-cover melted away earlier than usual from the lower part of the Nisqually Glacier, leaving the ice exposed for a longer period during the summer. That reasoning in any event seems consistent with the generally recognized fact that the summer-temperatures are as a rule the primary factor in the wasting of glaciers, and diminution of snowfall is a secondary factor.

The resurvey of Profile 1, which is located 3/4 mile above the terminus and at a mean altitude of 5,250 feet, showed that during the 13 months that had elapsed since the survey in 1943, the surface of the glacier had been lowered by amounts ranging from less than five feet at the debris mantled margins, to a maximum of 30 feet in the central strip which consists of fairly clean ice. Over a breadth of 1,500 feet the vertical reduction averaged 14.4 feet.

The exceedingly rapid wasting of the ice in the clean central strip, it should be explained, is due not merely to melting and evaporation, but also to the erosive action of a stream of melt-water which on warm summer days attains the proportions of a rushing torrent. As a result of this combination of destructive processes the central strip of the glacier, about 700 feet in width, is becoming more and more deeply concave, assuming the aspect of a valley. In 1942 the bottom of this valley was lowered 23 feet and in 1943 nearly 20 feet. In September 1944 the valley had attained a depth of 180 feet below the marginal portions of the glacier, thus closely rivaling the valley in the surface of the Eliot Glacier on Mount Hood, which in 1943 was about 180 feet deep [MATTHES and PHILLIPS, 1943] and since then has been deepened an additional 25 feet (see Eliot Glacier, below).

Comparison of the plotted profiles from successive resurveys reveals that in 1932 the valley in the surface of the Nisqually Glacier was still an inconspicuous feature only 60 feet in depth. Since then, however, the bottom of the valley has been lowered 150 feet, while the eastern margin of the glacier has been lowered 50 feet and the western margin 60 feet. The successive profiles show also that valley-deepening has been greatly accelerated during the last three years. Prior to 1941 the average rate per year was only nine feet, but since 1941 it has increased to 23 feet. If wastage continues at this rapid rate, the medial part of the glacier, which is now presumably less than 200 feet thick, will be destroyed in less than ten years. The debris-covered margins will be reduced more slowly, but they will not be important sources of runoff, and the flow of the Nisqually River in late summer and in autumn consequently will be greatly diminished.

At Profile 2, which is located 1-1/4 miles above the terminus and at a mean altitude of 6,000 feet, the resurvey in 1944 disclosed wastage almost as rapid as at Profile 1. Near the eastern margin of the glacier, where the ice is partly stagnant and deeply covered with rock debris, the changes were insignificant, but thence westward over a breadth of 1,000 feet, the ice surface had been lowered from five to ten feet, and in the axis of the valley, which here lies near the western margin, it had been lowered fully 25 feet. Over a total breadth of 1,900 feet the glacier had been reduced in thickness an average of 13.2 feet. JOHNSON'S estimate for the previous year was eight feet.

The successive resurveys of Profile 2 show that in 1932 the valley in the glacier's surface was still so shallow as to be hardly noticeable, but by 1941 its bottom had been lowered 73 feet, at a mean rate of eight feet per year, and by 1944 it had been lowered 45 feet more, at a mean rate of 15 feet per year. In 1944 the valley was 55 feet deep below the level of the flanking ice masses.

Profile 3, which is located at a distance of 1.9 miles from the terminus and at an altitude of 6,750 feet, marks the lower end of the relatively steep and intensely crevassed middle course of the glacier, and presumably reflects in some measure the changes that are taking place there. As has been noted in previous years, those changes sometimes are opposite in character to those that prevail in the lower course. Thus in 1943 the surface of the glacier at Profile 3 had risen several feet throughout its entire breadth. The ice stream had actually swelled, while it was shrinking rapidly in its lower course. In 1944, however, evidence of decided shrinkage was found at Profile 3 as well as at Profiles 1 and 2, the average being 8.2 feet. Only in the central and more active part of the glacier, over a breadth of 400 feet, did the ice maintain its former level. In one place it had even risen from five to ten feet. The excessive wastage, which heretofore was confined to the Nisqually's lower course, about 1-1/2 miles in length, therefore now appears to extend up into its middle course also, thus affecting the glacier over a distance of fully two miles. (The total length of the Nisqually Glacier in 1944 was about 4.4 miles.)

In addition to the foregoing measurements of surface ablation on the Nisqually Glacier, observations were made in 1944 on the displacement of marked boulders in order to determine the rate at which the ice is moving down the valley. At Profile 1 none of the boulders within the debris-covered zone near the eastern margin of the glacier appeared to have moved at all since 1943. Two boulders near the western margin had moved 25 feet down the valley and 25 feet toward the axis of the glacier, and a boulder situated in the valley in the glacier's surface had moved 60 feet at a large angle toward the axis. Unfortunately, the identification of that boulder in 1944 is open to doubt, and the figure cited therefore may not be reliable. It nevertheless seems to be of the right order of magnitude for this part of the glacier.

Of 18 boulders on the line of Profile 2 that were marked in 1943, seven were found again in 1944. They indicate movements of the ice increasing gradually from zero at the eastern margin to 73 feet at a point to the west of the medial line. Two boulders situated within the valley had been displaced 60 feet and 70 feet, respectively. There is little doubt, therefore, that in the vicinity of Profile 2 the more active ice is moving at rates ranging from 60 to over 70 feet per year.

None of the boulders on the line of Profile 3 that had been marked in 1943 could be located again in 1944, they having disappeared, presumably, in the numerous crevasses that open in this steeply descending and turbulent part of the glacier. Fortunately, however, HOWARD R. STAGNER, Park Naturalist of Mount Rainier National Park, succeeded in tracing the movements of several boulders on a line established a short distance above Profile 3, and his data, shown in Table 3, though covering a period of only 99 days, from July 11 to October 18, shed valuable light upon the rate of the ice movement in that part of the glacier.

Table 3--Movement of boulders on Nisqually Glacier, 1944

Number of boulder	Distance from eastern margin	Displacement from line of sight				
		July 11	July 25	Aug 11	Sep 7	Oct 18
	ft	in	in	in	in	in
1	65	0	0	23	62	90
2	340	0	71	151	329	612
3	460	0	93	242	444	724
4	750	0	129	292	511	881
5	950	0	120	300	520	809
6	1220	0	106	236	353	756
7	1490	0	65	186	190?	552?

Boulder 4, situated near the middle of the glacier, it will be seen, was displaced the greatest distance--881 inches, or 73.4 feet. In other words, in 99 days it was displaced as much as the most rapidly moving boulder on Profile 2 was displaced in 13 months. It is not to be supposed, however, that the boulders on STAGNER'S line move at the same rate throughout the year. The figures hold good only for the summer months, when the movement is fastest. The greatest speed was attained during the period from July 25 to August 11, and from then on the rate again declined. These facts are most clearly illustrated by measurements to boulder 5, which lay somewhat to the west of the medial line. From July 11 to July 25 it moved at a mean rate of 8.6 inches per day; from July 25 to August 11 it attained a maximum rate of 10.6 inches per day; then, from August 11 to September 7 the rate declined to 8.1 inches, and from September 7 to October 18 it fell to 7.0 inches. During the winter months the gravitational movement of the ice probably slows down still more. A conservative estimate of its variations with the seasons indicates a probable total for the year of not less than 200 feet.

In striking contrast with this large total is the small displacement of a boulder situated about 500 feet back of the Nisqually's terminal face. From July, 1943, to September, 1944, according to STAGNER'S measurements, that boulder moved forward only about 20 feet. The measurements by STAGNER and JOHNSON together, then, reveal a progressive slowing down of the gravitational movement in the Nisqually Glacier from 200 feet per year, at a distance of two miles from the terminus, to 70 feet per year at a distance of 1-1/4 miles, and to only 20 feet per year near the terminus itself. The sightseer who casually inquires "How fast does this glacier move?" probably little suspects that it makes a great difference at which point in the glacier's course the rate of movement is measured. Even to scientists it is somewhat of a revelation to find that the rate at the terminus may be only 1/10 of the rate at a point two miles up the glacier.

It is to be borne in mind, of course, that the displacement of boulders is not necessarily a true index of the rate at which the ice in a glacier moves, for boulders sometimes generate ice pedestals, by protecting the ice beneath them from the rays of the Sun, and eventually slide, or roll down again, usually in the direction of strongest insolation; besides, their positions may be changed by various happenings incidental to the lowering of the ice surface by ablation. This doubtless is so on the lower stretches of the Nisqually, where the ice wastes down from ten to 30 feet in the course of a year. Nevertheless, after due consideration of all the possibilities, there seems little reason to doubt that the measurements reported do indicate the general order of the movement at each profile line. Even if the figures reported are all plus or minus 25 per cent in error, they still demonstrate beyong possible doubt that the movement slows down progressively toward the terminus.

That such a slowing down occurs in many glaciers is a fact well known to glaciologists. It is especially pronounced in glaciers that grow progressively thinner toward their termini. Flattening of the slope of the bed and lateral spreading of the terminal portion of the glacier are in some instances contributory factors. In Europe many measurements have been made on stakes, or stones, placed in rows across glaciers, for the purpose of demonstrating those facts; but very good measurements of this kind have been made in the United States also. None is more instructive than those which the Research Committee of the Mazamas have made on the Eliot Glacier on Mount Hood [see especially Mazama, v. 7, no. 2, pp. 67-72, 1925; v. 8, no. 12, pp. 65-68, 1926; v. 9, no. 12, pp. 92-93, 1927].

JOHNSON'S and STAGNER'S observations on displaced boulders on the Nisqually Glacier, then, do not reveal anything that is fundamentally new, but they nevertheless have special value because the distances between successive profile lines are accurately known and it is therefore possible to calculate the rate at which the ice shrinks longitudinally as it moves. If the ice along the locus of maximum velocity in the Nisqually Glacier be conceived as forming a slender prism extending from the terminus up to STAGNER'S line--a distance of practically two miles--then, according to the observations cited, in 13 months, from August, 1943, to September, 1944, the upper end of this prism moved 200 feet down the valley, while the lower end moved only 20 feet. The prism as a whole, therefore, was shortened 180 feet, or 1.7 per cent of its length as of 1943 (not counting the loss in length due to the recession of the terminal ice face by ablation).

This longitudinal shrinking, however, was not uniformly distributed throughout the length of the prism. The lower segment extending from the terminus to Profile 2 in 1943 was 1-1/4 miles, or 6,600 feet, long. Its upper end moved 73 feet, while its lower end moved 20 feet. It therefore was shortened 53 feet, or 0.8 per cent. But the upper segment, from Profile 2 to STAGNER'S line, experienced much more rapid shrinkage. Its length in 1943 was 3/4 mile, or 3,960 feet. Its upper end moved 200 feet, while its lower end moved 73 feet. It therefore was shortened 127 feet, or 3.2 per cent.

It is not the intention here to discuss the significance of these variations in the rate of shrinkage, nor, for that matter, the cause, or causes, of longitudinal shrinkage in glaciers generally. To do so adequately would require a separate essay. Besides, the phenomenon is as yet very imperfectly understood, and an analysis of it must await further and more precise quantitative data than we now possess. However, since the measurements on the Nisqually and Eliot glaciers have served to focus attention upon the problem, it seems appropriate to stress the importance of its study, for it is part and parcel of the larger problem of glacier motion. Splendid headway in the exploration of the mechanics of glacier-motion have been made in recent years, chiefly (1) by microscopic study of the recrystallization of firn and glacier ice under differential stresses, and (2) by the development of the theoretical concepts of gravity-controlled and pressure-controlled flow, with shearing and overthrusting movements called forth by obstruction. The time has now come, it seems to the writer, to apply the new principles thus developed to the interpretation of those relatively obscure readjustments in the flow movement of a glacier that are induced by variations, secular as well as seasonal, in its alimentation on the one hand and in its wastage on the other hand. The most notable of these readjustments are in the form of wavelike surges set up by unusually heavy accessions of fresh snow in the firn basin-surges that travel down the length of a glacier at rates independent of, and far greater than, those of the normal gravitational movement of the ice. Under the present conditions of progressive ice depletion there is little opportunity for the observation of translatory surges, but there is in any case abundant opportunity for studying the effects on movement and longitudinal shrinkage that result from progressive thinning. For such studies the Nisqually should afford a good and readily accessible field, and it is to be hoped, therefore, that further and rather frequent measurements on movement as well as on ablation will be made on the Nisqually in future years. It is possible, moreover, that even under present climatic trends evidence of occasional surges will be detected in the middle and upper courses of the glacier--that is, at and above Profile 3--although such surges probably die out a short distance below that line.

In 1944 STAGNER again measured the frontal recession of the Nisqually and four other glaciers on Mount Rainier. As was explained in the Committee's report for 1943 [MATTHES, 1943], he has abandoned the commonly used method of making one linear measurement from a reference point, or base-line, to a selected point at the terminus--usually one at the mouth of the subglacial tunnel from which the stream of melt-water issues. Because of the irregular, often deeply embayed, form of the termini of the Rainier glaciers, that method hardly yields a measure of recession representative of the terminus as a whole, and, indeed, it has often indicated wide and sudden variations in the rate of recession from year to year that did not in the least reflect the general trend of glacier shrinkage. STAGNER therefore has adopted a new plan of making a plane-table map of the terminus each year, and of drawing on each map a line representing the "average position" of the ice front. The distance scaled off on the map between the average-position lines for any two successive years then indicates the value of the mean recession.

In 1943 STAGNER made the first plane-table maps of five glaciers on Mount Rainier. In 1944 he mapped them again and thus was able for the first time to test the value of his method. The results leave no doubt as to its superiority over the old method. One advantage of the STAGNER method is that it permits accurate mapping of both the top and the base of the terminal ice wall. Many of the debris-covered glaciers on Mount Rainier, including the Nisqually, end in a sheer ice wall from 50 to 100 feet in height, and the top line of such an ice wall is as a rule more sharply defined than the base, the latter being partly hidden by accumulations of rock debris. STAGNER therefore finds it convenient to draw the average-position line for the top rather than the base of the ice wall. By taking vertical angles to points on the top, moreover, he is able to determine the height of the ice wall and thereby also the thickness of the glacier at the terminus.

By the new method Nisqually Glacier was found to have receded on an average 79 feet since 1943. This amount happens to equal exactly that recorded for the period 1942-43. The general form of the terminus had not changed, but the ice wall in 1944 was more spectacular than at any time in the past four years. The wall was flanked on both sides by a projecting wing of stagnant, debris-covered ice. These residual masses were not considered in the determination of the "average-position" line. They may persist for many years to come, owing to the progressive thickening of their protective debris mantles. Since 1918, when the National Park Service began making annual recession measurements, the Nisqually Glacier has been shortened 1,923 feet.

Paradise Glacier is situated on a plateau instead of in a canyon, and is therefore free from surface debris and has a normally sloping terminus, without sheer ice wall. Measurements consequently were made to the toe of its terminus. As the lower end of the glacier was largely buried under snow in 1943 no recession measurements could be made in that year. The recession recorded in 1944--83 feet--therefore is set down as the sum of two years, though very probably it was effected largely or wholly during the summer of 1944.

As a result of its rapid shrinking, the glacier has lost the beautiful ice caverns which attracted many sightseers in former years. The glacier, moreover, has ceased to contribute water to the Paradise River and Sluiskin Falls, and now drains only into Stevens Creek.

Emmons Glacier, the largest and longest ice stream in the continental United States (length approximately 5.6 miles), offered a peculiarly difficult problem in the evaluation of its mean recession in 1944. Because of the collapse of the tunnel of a subglacial stream, an unusually deep embayment had developed in the right half of its terminus. It is evident from STAGNER'S maps for 1943 and 1944 that this embayment was deepened no less than 600 feet in one year. If it is regarded as a feature of the terminus, the average-position lines drawn by STAGNER would indicate a mean recession of 296 feet. But, for the unembayed part of the terminus, his lines indicate a recession of only 60 feet. Inasmuch as the embayment probably will be extended still far up along the right margin of the glacier during the next few years, and will become a marginal feature rather than a terminal feature, it seems best to disregard it in the measurements in 1944. Accordingly, the mean recession of the Emmons Glacier will here be reported as being 60 feet.

Carbon Glacier ends in an ice wall that extends across nearly the entire breadth of its terminus, and it consequently offers no problem in the evaluation of its recession. The latter, based upon the retreat of the top of the ice wall, in 1944 averaged 35 feet. The recession reported in 1943 was 45 feet.

South Tahoma Glacier in 1944 presented a broader and more clean-cut terminal face than in former years, but its terminus as a whole retained its chaotic aspect and remained in large part obscured by morainal debris. In drawing the average-position line, STAGNER deemed it best to disregard the bodies of half-buried, stagnant ice that flank the terminus on both sides. The mean recession for 1944 was estimated at 114 feet. In 1943 an advance of 17 feet was reported, but that advance, it should be understood, was more apparent than real. It resulted from the former practice of measuring to the point of exit of the subglacial stream, which in this case had shifted its position considerably.

In concluding this report on the glaciers of Mount Rainier it seems appropriate to point out that the sheer ice walls in which so many of them terminate are by no means ordinary features characteristic of glaciers in general. They are, on the contrary, rather unusual features whose significance has not yet been satisfactorily explained. Although it is evident that they develop only in debris-mantled glaciers, the ablation of whose upper surfaces is retarded by the protective covering, while the recession of the ice walls is not so retarded, the fact remains that ice walls are not invariably present in such glaciers. The Nisqually, for instance, had a normally sloping terminus in 1910 and 1911, when the writer beheld it, and, to judge from dated photographs, it must have had such a terminus for many years. The ice wall has developed chiefly during the last few decades, but the reason for its development is still a mystery. More observations and an intensive study of dated photographs will be needed before an explanation of the phenomenon can be attempted.

Glaciers of Mount Hood, Oregon

Eliot Glacier--KENNETH N. PHILLIPS, Chairman of the Research Committee of the Mazamas, reports that in September, 1944, triangulation measurements to the terminus of the Eliot Glacier revealed what appeared to be an advance of the ice of ten feet since September, 1943. However, as the ice at the terminus was concealed by a large snowdrift in 1943, no accurate measurement was possible in that year, and the recession of 33 feet that was then reported is probably erroneous. The measurement taken in 1944, therefore, should be compared with that taken in 1942. On that basis it may be concluded that from 1942 to 1944 there had been a net recession of 23 feet.

As in previous years, the mass of moraine-covered "dead ice" on the east side of the canyon, which projects at least 100 feet beyond the terminus, was not considered as forming part of the glacier any longer. This is in line with the practice followed in measuring the recession of glaciers on Mount Rainier.

The two profile lines across the lower part of the Eliot Glacier, which have been resurveyed annually since their establishment in 1940, were surveyed once more in 1944. On the lower profile line, the surface was found to have been lowered by ablation during the past year by amounts ranging from one foot at the margins to five feet in the center. On the upper profile line, where the ice is only scantily covered with morainal debris, ablation had been more rapid and the surface appeared to have been lowered as much as 25 feet near the medial line of the glacier. A large share of this lowering, however, is very probably attributable to the erosive action of a streamlet of melt water. Over a width of 900 feet, an average of 24 feet of ice has been lost during the period 1940-44.

On the lower profile, the gravitational movement of the ice was measured at eight points, and was found to vary from 10.2 feet to 18.9 feet in four years (2.6 feet to 4.7 feet per year). The unweighted average was 16.0 feet, or 4.0 feet per year. On the upper profile none of the marks set in 1940 could be found in either 1943 or 1944.

Coe Glacier, on the north slope of Mount Hood, was found on September 24, 1944, to have advanced somewhat from its 1943 position. Measurements to the point of exit of the stream indicated an advance of 20 feet, but at another point on the solid ice front there appeared to have been an advance of 60 feet. This would imply a very rapid gravitational movement of the ice in the Coe Glacier as compared with that in the Eliot Glacier, but that is not impossible in view of the steepness of the Coe Glacier's descent. In 1943 this glacier receded 19 feet, and in 1942 as much as 41 feet.

Glaciers of Rocky Mountain National Park, Colorado

Park Naturalist **RUSSELL K. GRATER**, on September 19, 1944, visited the Andrews and Tyndall Glaciers on the east side of the Continental Divide, whose variations have been under observation since 1932. As no measurements could be made in 1943, owing to the shortage of personnel in the Park staff, the data obtained in 1944 are compared with those of 1942.

Andrews Glacier in 1944 was found to have receded 97 feet from the point it reached in 1942. Its lower portion had shrunk to the proportions of a slender ice tongue hemmed in by slopes of rock debris. The narrowing of the ice tongue is indicated by the fact that in 1944 its northern margin had shrunk away 30 feet from a station that had previously been established close to the ice on that side of the cirque.

Tyndall Glacier appeared to have receded 56 feet since 1942, but no accurate determination could be made, as the ice disappears under chaotic masses of morainal material.

GRATER submits with his report a chart and a set of graphs from which it appears that the alternating advances and recessions of the Andrews and Tyndall glaciers correspond rather closely with the variations in snowfall and temperature recorded at the Longs Peak Weather Station since 1939. These data can not be given here in their entirety, but **GRATER'S** interpretation may be summarized as follows: Whenever the snowfall in winter aggregates 165 inches or more, and the ensuing summer is only moderately warm, the glaciers build up and advance; whenever, on the other hand, the snowfall is considerably under 165 inches and the summer temperatures are high (maximum over 80° F at Longs Peak Weather Station), the glaciers shrink and recede. So close is this correspondence in their behavior that for any year in which the glaciers were not measured it may nevertheless be possible, **GRATER** believes, to infer from the weather records alone whether the glaciers advanced or receded. Thus it seems probable, on the strength of the weather data for 1942-43, that in 1943, the year when measurements were omitted, the glaciers receded by moderate amounts. As the weather conditions in 1943-44 were closely similar to those in 1942-43, the recessions noted above for the period 1942-44 presumably can be divided evenly over the two years. Further observations extending over a longer period of years will, of course, be needed to demonstrate validity of such inferences.

Glaciers of Glacier National Park, Montana

Park Naturalist **M. E. BEATTY** appropriately opens his report on glacier measurements in September, 1944, with a brief statement regarding the weather conditions that prevailed during the preceding 12 months. At Belton, Montana, the administrative headquarters of Glacier National Park, snowfall during the winter of 1943-44 totaled only 46.2 inches, or about 40 per cent of the 30-year average of 117 inches. Precipitation during the entire 12 months was well below the normal; on the other hand, the mean temperature was appreciably above the normal. Both precipitation and temperature conditions therefore had a decidedly adverse influence on the glaciers, and the effect is readily apparent in the recession figures reported by **BEATTY**, which are about three to four times as large as those reported in 1943--in fact, roughly of the order that prevailed during the period of excessive wastage from 1936 to 1941.

The question was raised by former Park Naturalist **M. V. WALKER** in 1943, whether the glaciers in Glacier National Park might be expected to respond promptly to the fluctuations in precipitation and temperature that occur from year to year. In that connection it is to be borne in mind that these glaciers are now very short, measured in the direction of their movement. They average about 1/2 mile in length from bergschrund to terminus. In a year of heavy snowfall followed by subnormal summer temperatures, therefore, they may remain largely or even wholly blanketed with snow and suffer little or no ablation. Such was the case in 1943, and as a result recession then was minimized. In 1944, on the other hand, the snow cover was very light and during the warm summer it melted away over all but the highest parts of the glaciers. Ablation of the exposed ice must have been greatly increased, and that fact is reflected in the large recessions measured.

It seems appropriate here to emphasize again that, in general, the summer temperatures are the most potent of all the factors that affect the regimen of a glacier. The winter temperatures, on the other hand, matter very little. Snowfall, as a rule, is second in importance; if very great, it may sometimes offset the effect of the summer heat.

Following are the results of BEATTY'S measurements:

Sperry Glacier on September 4, 1944, had receded an average of 51 feet from the markers set in 1943. The photograph taken in 1944, as compared with one taken in 1943, shows very considerable shrinkage in the thickness and the breadth as well as in the length of the main ice tongue.

Jackson Glacier on September 5, 1944, had melted back irregularly, by amounts varying from zero at its eastern margin, which is shaded by the cirque wall, to 108 feet at its western margin, which is strongly insolated. The mean recession of the ice tongue, at the middle, was about 56 feet. Triangulation measurements to the large boulder on the ice which had been marked in 1943 showed that it had moved forward 30 feet during the year.

Grinnell Glacier on September 6, 1944, had receded by amounts ranging from 32 feet to 51 feet. The average recession for its entire front, which is 1.2 miles in length, was estimated to be 40 feet.

Agassiz Glacier, which is difficult of access because of the dense snow-bent brush that covers the mountain sides beneath it, could not be reached, but it was photographed from a spur of Mount Peabody--the same spur from which WALKER took a photograph in 1943. Comparison of the photographs shows clearly further progress in the destruction of this glacier, which once was the largest in the Park. The main mass appeared to have been shortened about 80 feet.

Glacier Recession in the Andes of Peru, and its Significance

It has been customary heretofore to restrict the reports of this Committee to the discussion of glaciers in the Continental United States and Alaska, but it seems appropriate this time to include also certain data on the glaciers in Peru, the reason being that those data are held to strengthen significantly the evidence for close synchronism between the variations of glaciers in the Northern and Southern Hemispheres.

The data in question are taken chiefly from a paper by J. A. BROGGI [1943 a], Director of the Geological Institute of Peru, in which he presents the results of his observations on the current recession of the glaciers and rise of the snow line in the Andes of Peru, together with a summary of earlier reports on those subjects.

From BROGGI'S summary it appears that the explorers, who visited Peru during the closing decades of the 19th century and the opening decades of the 20th, were generally agreed that the Peruvian glaciers receded about 150 to 200 meters in altitude in the course of some 50 years, and they noted that there is commonly a marginal zone about 300 meters in height from which, evidently, the ice has withdrawn quite recently. They mentioned, furthermore, well attested instances of a rapid rise of the snow line resulting in the complete deglaciation of lofty peaks that within the memory of local settlers had been perpetually covered with snow. A notable example is the Huaylillas massif, in northern Peru (lat. 7°-45′ S, long. 78°-03′ W). Those reports are in general borne out by BROGGI'S observations, but he finds that during recent decades deglaciation in the Peruvian Andes has progressed much more rapidly than during the period covered by the earlier explorations. A striking example of the recent acceleration of the upward shift of the snow line is contained in Table 4, relating to observations on Mount Huascaran (22,182 feet, lat. 9°-07′S, long. 77°-30′W), the highest peak in the Sierra Blanca, in northern Peru.

Table 4--Data on snow line on Mount Huascaran, Peru

Authority	Date	Névé line	Probable error	Rise
		m	m	m
Middendorf (photo)	1886	4320	±50	
Enock (photo)	1903	4420	±50	100
Peck (photo)	1906	4500	±50	80
Sievers (report)	1909	4750	±10	250
Borchers (map)	1932	4600	±10	-150
Broggi (photo)	1942	5100	±50	500
		Net rise of névé line, 1886-1942		780

A net rise of the névé line of 780 meters (2,640 feet) in 56 years will doubtless amaze glaciologists in the Northern Hemisphere. It approximates, in fact, the rise of the névé line in the European Alps which, according to PENCK and BRUCKNER'S estimates, followed upon the BUHL readvance of the glaciers during the closing stages of the Pleistocene epoch. One cannot help wondering whether a climatic swing of such amplitude really took place in the Peruvian Andes within the last 56 years--even if allowance is made for the proximity of those mountains to the Equator. The present writer suspects that some of the observers listed by BROGGI differed in their conceptions as to what constitutes the névé line, or the snow line, and applied different criteria in determining its altitude. As is evident from the literature, even the best informed glaciologists have failed to agree completely on the definition of the névé line and the snow line. The confusion of ideas on those subjects doubtless accounts for the discrepancies in the figures which different explorers have reported from various parts of South America for the altitude of what they loosely termed the snow line or névé line. (A brief discussion of the distinctions between the autumnal snow line and the climatic, or regional snow line, and between the regional snow line and the névé, or firn line on individual glaciers was presented in the report of this Committee [MATTHES, 1942].)

Particularly valuable, because of their indubitable authenticity, are the data cited by BROGGI for the recession of glaciers in the Peruvian Andes. His reproductions of dated photographs afford, indeed, clear ocular evidence. For instance, three successive pictures of the Abra Pincoyuyoc, in the Central Andes of Peru, present a truly spectacular record of rapid, and finally complete, deglaciation. The first picture, a water color sketch by the cartographer ANTONIO RAIMONDI, portrays the mountains as they appeared in 1862, heavily laden with snow and ice. Even if, as is quite possible, the sketch was made at a time of the year when much of the previous winter's snow still lay on the ground, it seems reasonably certain that the mountains in 1862 bore much glacier ice as well as seasonal snow. The second picture, a photograph taken by BROGGI in 1923, shows the same mountains bare, except for some névé fields at the higher levels; and the third picture, taken by BROGGI in 1942, reveals complete absence of snow and ice.

Progressive and ultimately complete deglaciation is recorded also in three photographs of Paragte Peak (lat. 10°-42'S, long. 76°-12'W), on the Continental Divide, which BROGGI took in 1917, 1923, and 1942, respectively. The first shows two fairly large cirque glaciers that are confluent at the base of the peak; the second shows them somewhat shrunken and only barely touching; and the third reveals the mountain group wholly bereft of snow and ice. BROGGI estimates that the glaciers in this case receded 500 meters in altitude in 25 years.

A vertical recession of 500 meters (1640 feet) in 25 years also may seem amazingly rapid, yet the case of the Paragte glaciers is not unique. As is evident from two photographs taken in 1903 and 1942, respectively, the Quebrada Llaca Glacier on the Ranrapalca group (lat. 9°-25'S, long. 77°-25'W) in 39 years retreated from an altitude of 4300 meters to one of 4800 meters. Glaciers on the Quebrada Quilcayhuanca are reported to have retreated upward 300 meters during the same interval. In this connection it is to be noted that the Blue Glacier on Mount Olympus, which was mentioned earlier in this report, made a vertical retreat of fully 1500 feet between 1919 and 1944. The steepness of the canyon wall over which the terminus of that glacier plunged was, of course, an important factor in this rapid upward recession, but the case is, nevertheless, of peculiar interest in that it shows that such rapid recession can take place even in latitude 48° N, and in mountains of moderate altitude, having a decidedly maritime climate with heavy precipitation--the very opposite of the continental climate of the northern and western ranges of Peru, which is characterized by scanty precipitation and strong insolation, because of the low latitude and the high altitude.

On the eastern ranges of Peru, which receive considerable precipitation from the southeast trade winds, glacier shrinkage appears to be progressing at a relatively moderate rate. That fact is readily apparent from two dated photographs of the Raura Glacier, which descends to Lake Santa Ana, the extreme head of the Marañon River, as determined by the surveys of O. M. MILLER [1929]. In 1943 the ice mass was only about 20 meters thinner than in 1927 and still fronted directly on the lake. Two other photographs, taken in 1921 and 1943, respectively, show a vertical recession of 70 meters at the steep left margin of the Raura Glacier and, in the background, a recession of about 100 meters at the front of the Caballococha Glacier. These changes are comparable in magnitude to those that have taken place during the same period in many cirque glaciers in the European Alps and in the western United States.

In the southern Andes of Peru, deglaciation is progressing at a still slower rate. The Misti-Chachani group (19,000 to 20,000 feet) in the vicinity of Arequipa (lat. 16° S), has lost but little of its névé cover during the present century. Comparison of photographs of El-Misti taken in 1910 and 1943, respectively, suggests a rise of the névé line of perhaps 50 meters.

In explanation of this contrast between the rapid deglaciation of the northern peaks and the almost inappreciable diminution of névé on the southern, BROGGI suggests that north of latitude 14° S, where a warm ocean current bathes the coast of Peru, warm air masses from the Pacific now penetrate farther than formerly into the Cordilleran belt, thereby pushing back the Amazonian rain front of the southeast trades. South of latitude 14° S, on the other hand, no warm ocean current reaches the coast, and climatic conditions on the Cordillera Occidental, of which El Misti and the Chachani massif form a part, remain almost unchanged.

Farther inland, however, the mountain ranges in the vicinity of Lake Titicaca are losing much of their snow and ice, probably chiefly as the result of decreased snow precipitation. That fact is evident from a set of notes by the engineer, **GEORG PETERSEN**, a copy of which **BROGGI** has kindly transmitted to the writer. Mount Ananea, **PETERSEN** reports, in April, 1945, seemed "far less impressive" than formerly, because of the marked reduction of its glacial mantle. A glacier on that peak, which in 1934 reached down to Lake Comuni, now ends several hundred meters from the lake and at a height of about 100 meters above it. In the lofty Sina Pass the central strip of snow-free land, which in 1933 was 1-1/2 kilometers wide, now measures fully five kilometers in width. Condoriquina Peak, which in 1934 still bore a splendid névé cap, now retains only an insignificant patch of snow. A long and massive glacier on Coarcuyo Peak, which in 1934 reached nearly to the road leading from Cuyocuyo to the Sayaco Pass, now terminates more than a kilometer from that road. A glacier that in 1934 fronted on a lakelet in the Aricoma Pass, between Crucero and Limbani, now ends at a considerable height above that lakelet. These and other similar observations by **PETERSEN**, although admittedly lacking in precision, nevertheless show clearly that in southeastern Peru deglaciation is progressing at a fairly rapid rate, so that the prospect is that, unless there is soon a return of heavier snow precipitation, many of the lofty "nevados" will lose their spectacular snow caps.

With these manifold evidences of progressive deglaciation **PETERSEN** would link the recent fall of the level of Lake Titicaca. So extremely low is that great lake at present that the outflowing Desaguadero River is reduced "almost to the proportions of a rivulet"--a circumstance which, it is to be noted, is of international concern, as the Desaguadero is the main feeder of Lake Poopó in Bolivia.

In summarizing, **BROGGI** makes the following points:

1. The data at hand, though scanty, nevertheless indicate unmistakably that in the Andes of Peru both glaciers and névé line have been receding to higher levels ever since 1862, or, roughly, since the middle of the 19th century.
2. Their recession was interrupted by a moderate re-advance between 1909 and 1932. Other oscillations probably have occurred from time to time, but definite records of them as yet are lacking.
3. The estimates of glacier recession, of the order of 150 meters in altitude in 50 years, reported by the earlier observers, probably are too conservative, for it is evident from dated photographs that in the Northern Andes some glaciers have receded vertically as much as 500 meters in the last 39 years, and in the Central Andes some have receded 500 meters in only 25 years.
4. There is no doubt, however, that since 1932 deglaciation in the Peruvian Andes has been sharply accelerated. This acceleration has been most marked in the northwestern ranges and least marked in the southwestern. It is attributed to diminished precipitation as well as rising temperatures due largely to the influx of warm air masses from the west.
5. These climatic changes are believed to be responsible, also, for the recent occurrence of short-lived but disastrous floods in several valleys at whose heads glaciers are situated. Those floods are held to be due to the bursting of moraines that enclose lakes at, or near, the fronts of the glaciers; but the failure of these moraine dams, nevertheless, is attributed not to the pressure of unusual accumulations of melt water, but to the thawing of the ice within the moraines. The phenomenon is discussed by **BROGGI** in another paper [1943 b].

From the writer's point of view, the data on the current deglaciation of the Peruvian Andes which **BROGGI** has brought together are valuable for two reasons: (1) because they are sufficiently complete to confirm in a substantial way the reports of earlier observers on the recession of glaciers in widely scattered parts of South America; and (2) because they reveal that the progress of deglaciation in Peru since the middle of the 19th century has closely paralleled the history of glacier recession that is so fully recorded in the European Alps and less completely in Scandinavia, Iceland, and the United States. The Peruvian data thus greatly augment and strengthen the evidence for synchronism between the variations of glaciers, and therefore also between the climatic variations, in the Northern and Southern Hemispheres.

Regarding the first point, it surely is not unfair to say that the scattered observations of the earlier travelers, which heretofore afforded the only information on the behavior of South American glaciers, were largely of a casual sort, uncoordinated, and sometimes unconvincing, especially when they conflicted with the reports of other travelers on the rise or depression of the ever elusive snow line on the mountains. Now, however, taken together with BROGGI'S well-authenticated and consistent data from the Peruvian Andes--the heart of the South American cordillera--the scattered earlier observations in the aggregate assume considerable significance, indicating beyond possible doubt--an exceptional case such as that of the Moreno Glacier, near Lake Argentino notwithstanding--that for many decades past deglaciation has been in progress more or less constantly throughout the length of South America, from Patagonia north to the Sierra Nevada de Santa Marta in Colombia.

As for the parallelism between the recessional histories of the glaciers in Peru and of those in Europe and North America, this can hardly be a mere coincidence. As has been shown by THORARINSSON [1940], from a comprehensive survey of data from all parts of the world, glacier shrinkage has been general since the middle of the 19th century, in both the Northern and Southern Hemispheres. It appears to be a world-wide phenomenon, the few exceptional cases comprising only a negligible fraction of the total number of ice bodies involved. For the Southern Hemisphere, it is true, THORARINSSON in 1939 had only scanty recession data, but, coming as they did from all three of its main glacier districts--the Andes of South America, the Alps of New Zealand, and the Antarctic Continent--they sufficed to be conclusive, though perhaps not convincing, to those who insist that for astronomic reasons the climatic cycles in the two hemispheres must be in opposite phase. But now BROGGI'S data from Peru reinforce the evidence for South America beyond the point of reasonable doubt, and this is all the more significant as SPEIGHT'S latest data [1935, 1940, 1941] have done the same for New Zealand, a region whose maritime climate is the very antithesis of the arid climate of the northern and central Andes of South America.

To consider these several glacier histories in detail would lengthen this report unduly, but it is worth while here to sketch the general pattern of European and North American glacier history since the middle of the 19th century, for comparison with the recession records in Peru and New Zealand. The 1850's marked a definite turning point in the behavior of the European glaciers. Prior to that time, for fully 300 years they had been oscillating forward and backward at frequent intervals, the major advances being unquestionably the greatest that have occurred since the end of the Pleistocene epoch [KINZL, 1932]. From the 1850's to the present time, on the other hand, recession has been dominant. Although interrupted by a moderate re-advance around 1890, and one or more lesser ones between 1910 and the early 1930's, in which many glaciers did not participate, this recession in the main has proceeded by successive stages of increasing rapidity, attaining its greatest acceleration during the last ten years. Those facts are strikingly brought out in MERCANTON'S graphs [1939] for the major glaciers of Switzerland and in THORARINSSON'S graphs [1940] for the glaciers of Norway, and [1943] for the glaciers of Iceland. That in the western United States, also, recession has been dominant since the 1850's, is definitely indicated by the record of the Nisqually Glacier on Mount Rainier [MATTHES, 1942, p. 385], and is to be inferred for glaciers on other peaks from reports and photographs dating as far back as 1870. As is evident from the more numerous and more precise observations during the present century, some, but not all, of the glaciers have made feeble and brief re-advances during the 1920's and the early 1930's, but on the whole they have continued to recede at an accelerated tempo up to the present time. Already several small cirque glaciers have disappeared [PHILLIPS, 1938].

Turning now to the Southern Hemisphere, it is clear from the reports of RUSSELL [1937] and SPEIGHT [1935, 1940, 1941] that the glaciers of New Zealand have lost enormously in length and in thickness since the 1860's, when the first observations were made. They regained much of their volume in the early 1890's, and made occasional small re-advances from around 1906 to as late as 1934, but since then they have been wasting away, at first slowly, then at an "abnormal" rate. Within six years their lower portions have been reduced 150 to 200 feet in thickness. The close analogy of this history of glacier shrinkage with that reported from Peru by BROGGI is manifest. The Peruvian glaciers also have been greatly reduced in length and in thickness since the 1860's; they made moderate gains between 1909 and 1932; and since then they have shrunk at an accelerated rate, some of them vanishing altogether. Thus, it will be seen, not only has glacier shrinkage been general in both Hemispheres during the last 90 years, but even some of the lesser variations during that period have synchronized rather closely. Most remarkable is the synchronism of the latest phase--the sharply accelerated recession during the later 1930's. THORARINSSON characterized it as "catastrophic;" SPEIGHT termed it "abnormal" and "phenomenal"(personal communication dated December 31, 1940), and BROGGI calls it "unusual" (aceleración inusitada).

One need not feel perturbed, in this connection, by PASCHINGER'S conclusion [1912] that the climatic cycles in the Northern and Southern Hemispheres are in opposite phase. That conclusion--which BOWMAN [1916] accepted without examining into its validity--was based upon an uncritical interpretation of scattered observations on the fluctuations of the snow line in different parts of the world, chiefly during the 19th century. Aside from the fact that many of those observations are not comparable on equal terms, because of differences in conception among the explorers as to what constitutes the snow line and as to the criteria by which its altitude should be determined, PASCHINGER neglected to check and correlate the snow-line data he had collected with the better authenticated records of glacier oscillations in the European Alps, which reflect in considerable detail the sequence of climatic variations in central Europe throughout the 19th century, and throughout the 18th and 17th as well. Had he consulted RICHTER'S painstaking compilation of data on glacier oscillations [1891], noting for each advance the time of its beginning as well as the time of its culmination, he doubtless would have discarded the notion of a 35-year cycle, and he would have realized that many of the snow-line observations have little value, because they were not timed to fall in the years of maximum or minimum elevation of the snow line, but were made in whatever years the explorers happened to visit the mountains, and often at such long intervals that they "straddle" the peaks and troughs of the climatic curve.

To cite but one example: on p. 92 he states, "Whereas in the Northern Hemisphere the snow line was low at the beginning of the 1870's and high after 1890, in a large part of the Southern Hemisphere, notably in South America and in the South Island of New Zealand, south of latitude 38° S, the snow line was, on the contrary, high between 1860 and 1870, and low after 1885." However, to any one familiar with the European glacier records, it will be apparent that this interpretation was made without knowledge of the fact that in the Alps the 1860's constituted the period of high snow lines and strong glacier recession that followed the great glacier maximum of 1848 to 1855; also, that already in the early 1870's the snows again began to pile up on the Alps in preparation for the re-advance, which in some places set in as early as 1874 and generally culminated around 1890. After 1890, on the other hand, the snow line must have risen again, for the glaciers receded slowly or remained stagnant for some time. The data from South America and New Zealand, which PASCHINGER cites, accord very well with this sequence, and, indeed, might have been selected to demonstrate synchronism in the two Hemispheres instead of the opposite.

In conclusion, it may be appropriate to point out why the proofs of synchronism between the recent glacier oscillations in the Northern and Southern Hemisphers, which have been materially strengthened by BROGGI'S and SPEIGHT'S observations, are held to be of far-reaching significance:

1. They warrant the inference that the causative climatic variations during the past 90 years affected both Hemispheres simultaneously, and not in alternation.
2. As these recent variations have been of a minor order, it may reasonably be supposed that the more pronounced variations during the post-Pleistocene interval also were synchronous in the two Hemispheres. These included, first, the warm period that culminated in the "climatic optimum" and caused widespread deglaciation, and, later, the cooler period that resulted in the re-expansion of the glaciers observed in Europe during the last three centuries.
3. There is even stronger reason to suppose that the major climatic variations of the Pleistocene epoch, which caused alternating glaciation and deglaciation on a continental scale, were synchronous in the two Hemispheres.
4. It follows, further, that whatever the causes of these climatic variations of different orders may be, the synchronism of their effects in the two Hemispheres rules out all theories, such as the so-called "astronomic theories" of CROLL, SPITALER, and MILANKOVITCH that demand refrigeration of one Hemisphere and simultaneous warming of the other. Although the mathematical verity of those theories is not necessarily impugned, it is abundantly evident that the causes of climatic change, which they postulate, are wholly subordinate to certain other, far more potent, but as yet undetermined, causes.
5. And, finally, it follows that all the calculations of glacio-eustatic changes of sea level that are based upon the assumption of synchronous glaciation and synchronous deglaciation of the two Hemispheres stand upon an essentially sound premise.

In view of the foregoing, glaciologists everywhere doubtless will be interested to know that BROGGI and his associates intend to continue their systematic studies of Peruvian glaciers in future years. The observations reported thus far are to be regarded as only a beginning. Photographs taken annually from definitely marked stations probably will constitute the main record, at least, for the less accessible ice bodies, but it is hoped that it will be found possible, also, to make instrumental measurements to glaciers that can readily be reached from routes of transportation. The photographs and other data thus secured are to be kept in orderly files for future reference. It is the writer's belief that these files in the course of time will form a source of factual information on the glaciers of Peru, comparable in scientific value to the statistical data on European glaciers that for many years have been collected by the International Glacier Commission. They, no doubt, will be highly appreciated also by its successor, the International Commission of Snow and Glaciers, which was created by the International Association of Scientific Hydrology at its general assembly in Washington in 1939.

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U. S. Geological Survey,
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REPORT OF THE COMMITTEE ON PRECIPITATION, 1945

Merrill Bernard, Chairman

Carlos Cabral
A. R. Codd
Leonard B. Corwin
Glen N. Cox
Robert W. Gay
W. G. Hoyt
J. W. Hower
Charles R. Hursh
J. Otis Laws
Luna Leopold
F. T. Mavis
A. K. Showalter
Waldo E. Smith
C. W. Thornthwaite

Progress in the observation of precipitation and the analysis of precipitation data has been sustained throughout the past year.

H. L. COLLINS (reporting on the network of precipitation stations, including those with automatic recording gages operated cooperatively by the Weather Bureau and the Corps of Engineers)--Beginning shortly after the Weather Bureau was established in 1891, precipitation data have been collected from a nation-wide network of climatological stations. Records from approximately 6,500 stations are published each month in Climatological Data compiled at 43 Weather Bureau Offices in the United States and Territories. Approximately 5,800 of these stations are maintained by the Weather Bureau, and the remainder are operated by other Federal, state, and municipal agencies, and private interests.

In 1940 the Weather Bureau, in cooperation with the Corps of Engineers of the United States Army (and the Department of Agriculture, 1941-42), began the establishment of an additional network of hydroclimatic stations, most of which are equipped with recording rain gages, to supplement the existing climatological network. The hydroclimatic network is now comprised of 3,023 stations, of which 2,367 are equipped with recording rain gages. In addition to these, records are obtained from approximately 400 recording and 1,000 non-recording gages maintained by other Federal, state, and municipal agencies, and private interests. Thus, records are available in the monthly Hydrologic Bulletins from approximately 4,400 stations, making a total of about 10,400 records available in the two publications of the Weather Bureau.

Since 1937 existing Weather Bureau networks of river and rainfall stations have been expanded in cooperation with the War Department in order to make available to the Corps of Engineers more frequent reports of river stages and rainfall. Reports are currently available from approximately 1,500 stations in the principal river basins of the United States. Of these stations, 485 are operated in cooperation with the Corps of Engineers in the following networks:

Ohio River
Lower Mississippi River
Upper Mississippi River
Willamette River
Yazoo River
Red River
Puyallup River
Los Angeles, Calif.
Connecticut River
Merrimack River
Mobile, Ala.
Lower Arkansas River
Middle Arkansas River
St. Francis River
Wallace Lake Reservoir (in La.)
Snake River (under development)
Delaware River (under development)

This, and the previous war years, produced a vast store of processed precipitation and related data for all the far-flung theaters of war. The Army Air Force, the Navy, and the Weather Bureau, resorting to modern mechanical methods of machine analysis, have made it possible ultimately to develop a global atlas on climatology which will reveal much that we have not known of climate in many quarters of the Earth.

LUNA B. LEOPOLD (reporting on another important by-product of the War in which the forecasting of precipitation has an important role)--During the last three years the United States Army has conducted an extensive program for training meteorological officers. The courses have been given at certain universities throughout the country and at a central Army training center. This program is certain to result in a much wider interest in meteorologic and hydrologic problems after the war, not only on the part of the large number of individuals who have been trained in the program, but also on the part of the public which has watched this program develop at its universities.

The Army personnel were given a full academic year of professional work in meteorology. It is of interest to note that even though forecasting of precipitation is a primary job of a meteorologist, the techniques taught even at the foremost schools deal with precipitation forecasting in the most qualitative terms. This emphasizes an important research problem to those interested in hydro-meteorologic research. Primarily because of the lack of techniques for quantitative forecasting of precipitation, the hydrologic aspects of this forecast problem were not even mentioned in the professional meteorological course.

On the other hand, the Army Air Forces Weather Service has been conducting a forecast-verification program designed to evaluate the accuracy of short-range forecasts currently made at field weather stations. One of the factors being evaluated is the quantity of precipitation which is forecast. In the short-range verification program the amounts of precipitation forecast are compared with the actual fall. The verifications are also compared with those which would have resulted if either persistence or climatology alone had been used as the forecast.

That this survey of the reliability of forecasts should include the testing of the accuracy of quantitative precipitation forecasts is an indication of considerable foresight on the part of the Weather Service. By the collection of such basic data on the reliability of forecasts, a back-log of information will be built up which will probably prove of considerable importance to hydrologists in the post-war period. Moreover, it will accentuate the need for more basic research.

The Army Air Forces are also cognizant of the importance of various phases of the field of hydrology. In refresher courses for weather officers, classes are conducted in the practical applications of hydrology to Army operations. A certain amount of time in these courses is devoted to the relation of precipitation to river stage and to the estimation of flood-peak discharges by use of the unit-hydrograph.

A. K. SHOWALTER (reporting concerning progress during the year in the cooperative program of the Corps of Engineers and U. S. Weather Bureau for organization of storm rainfall)--Pertinent Data Sheets summarizing depth-area-duration data for a portion of the processed storms will shortly be published by the Corps of Engineers.

The Hydrometeorological Section of the Weather Bureau is completing an extensive report on thunderstorm rainfall. This report will include a comprehensive bibliography, a digest of theoretical and factual knowledge of thunderstorm mechanisms, an exhaustive statistical-climatological survey of thunderstorms and associated precipitation with emphasis on seasonal and diurnal variations, a statistical analysis of the density-reliability ratio for rain gage spacing, and typical depth-duration-area relationships for thunderstorm rainfall. This report will be published as Hydrometeorological Report No. 5.

Possible practical applications of the theoretical developments of the Hydrometeorological Section were discussed by A. K. SHOWALTER in two papers on Quantitative Rainfall Forecasting in the April and September 1944 issues of the Bulletin of the American Meteorological Society.

MERRILL BERNARD--The cooperation between the University of Nevada and the Weather Bureau at Soda Springs, California, has continued during the past season. Investigations, in which the Sacramento District Office of the Corps of Engineers participated, have been directed toward the improvement of what has come to be called the "Sacramento" type snow gage. The container has the capacity to hold an entire season's precipitation without reducing the effectiveness of the calcium chloride brine used as the melting medium. The gage is equipped with the Alter-type flexible windshield and is designed structurally to withstand the severe conditions under which the gage is exposed at high elevations.

The Weather Bureau, in cooperation with Iowa State College at Ames, Iowa, and under the direction of H. C. S. THOM, Official in Charge at Des Moines, is conducting investigations of precipitation-gage networks, seeking optimum spacing and density under a wide range of storm conditions.

During the year the Weather Bureau has begun active planning for a special research project on thunderstorm structure. The project, still in a planning stage, will begin actual operation near Orlando, Florida, during March 1946. The primary goal is a better knowledge of the dynamics of thunderstorms for improved forecasting and greater safety for air travel. Various types of radar, air reconnaissance and numerous special pieces of equipment will be used. Special observations of thunderstorm precipitation will be made and should prove valuable to hydrologists.

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Washington, D. C.

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REPORT OF COMMITTEE ON GROUND WATER--1944-1945

S. W. Lohman, Chairman

H. F. Blaney	C. E. Jacob	N. A. Rose
E. B. Burwell, Jr.	G. W. Musgrave	Max Suter
Willard Gardner	A. M. Piper	C. V. Theis
C. S. Howard	Roger Rhoades	L. K. Wenzel

Because of war-imposed responsibilities of most agencies and individuals this year, no new programs were undertaken by the Committee, but the work of the Subcommittee on Permeability was continued, and a substantial progress report by C. E. JACOB, Acting Chairman, and by members of this Subcommittee follows this report as Appendices A to D.

Following a suggestion by MAX SUTER, copies of this year's Committee report were sent to each member prior to publication and it is planned to follow this procedure in the future.

JEAN M. BERDAN (U. S. Geological Survey, Washington, D.C.) has again prepared a list of current publications concerning ground water, which is given in Appendix E.

O. E. MEINZER (U. S. Geological Survey, Washington, D.C.)--A series of five papers forming a symposium on the subject of artificial recharge was scheduled for the annual meeting of the Society of Economic Geologists which was to have been held in February but which was cancelled on account of the traffic situation. The abstracts of these papers should appear in an early issue of Economic Geology and the complete papers will be published in Economic Geology later. I believe this series of papers will constitute a substantial contribution on the large and important subject of artificial recharge.

Probably the most important research activity of the Ground-Water Division during the year has related to further studies of ground-water hydraulics by the pumping-test methods. New and important developments of these methods are being made and further progress is being made in the interpretation of the results of the pumping tests in terms of geologic structure and consequent ground-water conditions. C. E. JACOB has been assigned to the Washington office and, in the absence of L. K. WENZEL, he has taken charge of this kind of investigation. Important tests have been made in the Fernandina area, Florida, under the direction of H. H. COOPER; in Oklahoma under the direction of E. C. REED; in the Memphis area under the direction of R. G. KAZMANN; in Indiana under the direction of J. G. FERRIS; in the Lansing area, Michigan, under the direction of W. T. STUART; and also in other places.

There is much interest in the plan of recharging through wells with cold water from municipal supplies during the winter season. The recharge with cold city water in Louisville in the early part of 1944 was accomplished under careful observation by W. F. GUYTON, in charge of the ground-water investigations in Louisville, and the significant results that were obtained are briefly described in a paper by GUYTON that was published in Water Works Engineering, v. 98, no. 1, January 10, 1945.

Considerable additional work has been done on the important subject of developing water supplies from wells that are situated so near to a surface stream that they obtain recharge from the stream. Further study of this subject has been made on several installations near the Ohio and other rivers by JEFFORDS, KAZMANN, FERRIS, GUYTON, and SCHAEFER. Similar studies are being made by the Army Engineers in order to determine the amount of seepage under levees and dams. LOHMAN and FISHEL have been in touch with some of this work. Attention should be called to the recent paper by JEFFORDS in the Journal of the American Waterworks Association, v. 37, no. 2, February 1945. Installations for developing water supplies by induced infiltration from streams have several attractive features which are likely to make this type of water supply increasingly important in the future. Although there is considerable seasonal fluctuation in the temperature of the water, the maximum temperature remains substantially lower than the maximum temperature of the adjacent stream. Moreover, the accumulating data indicate that where the wells are not too near the river, effective filtration occurs not only with respect to the suspended matter, but also, it appears, with respect to bacteria and odors caused by phenol wastes, etc.

The Committee on Rural Sanitation, under the sponsorship of the United States Public Health Service, has made substantial progress on its present project of preparing a concise report on the sanitation of rural water supplies. As the rural water supplies are obtained chiefly from wells, this report deals largely with the sanitation of ground-water supplies and the Ground-Water Division is cooperating in the preparation of the report. In connection with the regular work of the Ground-Water Division a considerable amount of reliable data are accumulating on the effectiveness of natural filtration at specific ground-water installations.

Considerable study has been given during the year by different members of the Ground-Water Division to the utilization of electric logs and surface-resistivity surveys in connection with ground-water investigations. Some good results have been obtained by the use of resistivity methods in connection with the development of water supplies for military purposes.

An intensive investigation has been in progress of the water consumed by phreatophytes, chiefly salt cedar, in the Safford Valley, along the upper Gila River in Arizona, and the effects of the transpiration loss upon the hydrologic cycle. A detailed report on the results of this investigation has been prepared by GATEWOOD, ROBINSON, COLBY, and HEM. [See also statement by ROBINSON.]

Mention should be made of the intensive study that has been in progress on recharge by rain- and snow-water penetration in the area that furnishes the public supply of Wichita, Kansas. Thorough investigation of recharge by the downward movement of soil moisture is greatly needed. Such an investigation should include mathematical studies and laboratory tests as well as field studies.

H. F. BLANEY (Soil Conservation Service, Los Angeles, California)--In connection with irrigation and evapotranspiration studies, the Division of Irrigation, Soil Conservation Service, continued cooperating during 1944 with the California State Division of Water Resources and the United States Geological Survey on observations of ground-water fluctuations in the lower San Luis Rey Valley, California. Some similar studies were continued along the Santa Ana River below Prado Dam in cooperation with the Orange County Water District and the United States Geological Survey for the purpose of determining the amount of water that might be conserved for irrigation.

The Division of Irrigation continued drainage studies of irrigated lands in Imperial Valley in cooperation with the Imperial Irrigation District and other agencies. Water-table fluctuations in shallow wells and ground-water flow from tile drains were measured. Measurements of the coefficient of permeability were made of representative sub-soils at different depths by laboratory and field methods. Techniques and formulas developed are described in a paper presented at the South Pacific Regional Meeting of the Section of Hydrology, American Geophysical Union, February 1945, Los Angeles, entitled "Soil Permeability as a Criterion for Drainage Design," by V. S. ARONOVICI and W. W. DONNAN [Trans. Amer. Geophys. Union, v. 27, no. 1, pp. 95-101, 1946]. Also the use of piezometers in water-logged areas to determine the flow pattern of ground-water seepage from irrigation canals and other sources, is discussed in a paper on "Ground-Water Determinations" by W. W. DONNAN and J. E. CHRISTIANSEN, published in the Western Construction News, November 1944.

During the year cooperative water-spreading investigations were continued in the upper San Joaquin Valley to determine the feasibility of recharging ground-water supplies by spreading off-season water from the proposed Friant-Kern Canal of the Central Valley Project, California. The agencies conducting this investigation include the Division of Irrigation of the Soil Conservation Service, Bureau of Reclamation, California State Division of Water Resources, United States Salinity Laboratory, and local districts.

The coordination of observations on ground-water levels by local agencies in the South Coastal Basin was continued by the California State Division of Water Resources. In September 1944 this Division issued Bulletin No. 39-J, "South Coastal Basin Investigation - Ground Water Levels 1941 - (Including San Jacinto and Antelope Valleys from beginning of record)." Ground-water studies were also started by the State Division of Water Resources in the Salinas Valley in central California.

The United States Geological Survey continued some excellent ground-water investigations in California during 1944, and it is presumed that some members of their staff will submit a report on this work.

E. B. BURWELL, Jr. (Office of the Chief of Engineers, War Department, Washington, D. C.)--Ground-water investigations were continued over a wide area of Florida in connection with studies made for a barge canal. Approximately 150 observation wells in the Ocala limestone were measured semi-monthly throughout the year. Records showing the elevation of the water-table or piezometric surface in these wells have been kept over the thirteen-year period, 1932-1944 inclusive.

Pumping tests were made at Dunnellon, Florida, to throw light on problems of unwatering locks during construction and the effects of unwatering on the ground-water conditions.

A symposium on underseepage and its control, in connection with the construction and operation of earth dams and levees, was held at Cincinnati, Ohio, in June, 1944. The papers and discussions have been published by the United States Waterways Experiment Station, Vicksburg, Mississippi, under the title "Conference on Control of Underseepage."

Limited investigations of ground-water elevations were made in connection with the exploration of reservoir sites in numerous river basins, including the Pecos and Rio Grande Basins in New Mexico, the Osage Basin in Missouri, the Republican Basin in Nebraska, the Brazos Basin in Texas, and the Cumberland Basin in Tennessee.

WILLARD GARDNER (Utah State Agricultural College, Logan, Utah)--Our attention in the Physics Department has been given in recent years largely to the dynamics of erosion. However, we are interested in the possibility of amplifying the DARCY law in order that it may be applied to the movement of moisture in unsaturated soils. It is presumed that the effective permeability must decrease as the moisture content decreases and it is hoped that we may find a simple relation between the permeability and the moisture content that may be sufficiently accurate for practical purposes [see Report of Committee on Infiltration, 1944-1945, Trans. Amer. Geophys. Union, v. 27, no. 1, pp. 125-138, 1946].

Interesting results have been presented by O. W. ISRAELSEN on his canal-lining studies in Experiment Station Bulletin 313 and in a technical paper in press. He contemplates investigating the possibility of drainage by pumping in the Millard County area. This will be a cooperative project in which the United States Salinity Laboratory at Riverside will participate.

Some soil-moisture studies are being begun by OMER J. KELLEY, representing the Bureau of Plant Industry, who contemplates studying the relation of soil-moisture levels and soil fertility.

An outdoor irrigation laboratory is being constructed by C. W. LAURITZEN, representing the Soil Conservation Service. He contemplates model tests to determine the practicability of various canal-lining materials.

I have been asked to participate in a discussion of infiltration with several others presented in a report of a Subcommittee on Soil Physics to form a part of the report of the Committee on Infiltration of the American Geophysical Union [Trans. Amer. Geophys. Union, v. 27, no. 1, pp. 125-138, 1946]. BYRON SHAW is the Chairman of this Subcommittee.

Comments by the Chairman--G. W. MUSGRAVE, V. C. FISHEL, and S. W. LOHMAN have had several discussions and some correspondence during the year relative to planning "ideal" experiments to be conducted cooperatively by the Soil Conservation Service and the Geological Survey, Water Resources Branch, Division of Ground Water in order to study the infiltration of water downward from the land surface through the root zone and the zone of aeration to the underlying water table. MUSGRAVE has completed preliminary plans for quantitative determinations of infiltration down into the zone of aeration and has suggested that these and the companion ground-water studies be carried out in a minimum of four types of regions as follows:

1. Humid climatic type 2. Subhumid climatic type	Same approximate latitude
3. Northerly latitude 4. Southerly latitude	Same climatic type

He suggests that "each regional experiment could properly include studies on two or more soil conditions (at least a permeable soil and a soil of relatively low permeability). Also it should include studies beneath two or more vegetal cover conditions (at least a dense and a sparse vegetal cover)." FISHEL has been working on plans for the companion ground-water studies to determine quantitatively the amount of recharge received beneath the experimental plots and its relation to the amount of infiltration. It is my hope that in some of these experiments it may be possible to isolate by means of sheet piling or other devices a limited area of a shallow aquifer so as to exclude the effect of the lateral movement of ground water. It this way measured increments of ground-water storage could be attributed solely to infiltration on the isolated plot. We shall welcome suggestions for carrying out such experiments, and hope that at least a beginning may be made in the not too distant future.

A. M. PIPER (U. S. Geological Survey, Portland, Oregon)--The ground-water work directed by POLAND from the office at Long Beach, California, has delved into fundamental principles of general interest. A report on geologic features of the Long Beach-Santa Ana area has been completed[a], to establish the physical background for hydrologic and geochemical conditions that are rather complex and that have not been clarified heretofore. A report on the chemistry of the ground waters which is in an advanced stage of preparation will develop the geochemical relations between hard, calcium-bicarbonate waters and soft, sodium-bicarbonate waters; will describe certain profound chemical modifications in native fresh waters that have been invaded by salt waters; and incidentally, will introduce a new graphic method for depicting the progressive contamination and chemical modification. The investigation in this area has dealt primarily with problems of salt-water encroachment; an investigation of the same problems now is being extended northwestward into the Torrance-Santa Monica area, in part of which the conditions have been aggravated by very large withdrawals of water for war industries.

In this work at Long Beach, invaluable basic conclusions have been derived from the electric logs of numerous oil-test wells. The Geological Survey, by establishing itself in the confidence of the several oil companies operating in the area, has had access to confidential, "grass roots" logs which clarified many obscure features of stratigraphy, structure, and water-occurrence. Probably only rudimentary progress yet has been made in the interpretation of such logs with respect to ground-water problems, and in understanding their limitations.

Early in 1945 the Long Beach Office began a dual-objective study along the Rio Hondo and the Los Angeles River from Whittier Narrows essentially to the coast for the United States Engineer Office at Los Angeles. The more immediate objective was to ascertain what construction problems, if any, would be created by ground-water conditions along certain proposed works for river-channel improvements. The broader objective is to appraise all potential effects of the channel improvements on the regimen of the several ground-water bodies, of which the principal confined body is utilized very extensively. It is indeed gratifying that the Engineer Office recognizes the regimens of the stream and of the ground-water bodies to be inseparable in this area.

Also in southern California, the inventory of ground-water resources over all of Santa Barbara County by UPSON and co-workers has been brought nearly to completion. Here, ultimate full utilization of ground-water bodies is a substantial element in plans for the optimum development of agricultural areas, which are being formulated by the county through cooperation with various Federal agencies. With respect to hydrology, the most fundamental finding relates to two ground-water areas superficially much alike; in one the replenishment is derived only in small part from the principal stream whereas in the other the replenishment is very largely so derived. In the one area is there hydraulic continuity vertically only locally between the several water-bearing zones, but in the other such hydraulic continuity is very extensive. Thus, with respect to the first of these two areas, the concepts of hydrologic character heretofore accepted, also of the desirable regimen for effective utilization of the water resources now must be fundamentally modified.

In the Pacific Northwest, research in ground-water hydrology has been handicapped most severely by loss of personnel. Currently and for the past year, effort has been directed primarily toward the completion of reports based on previous field work.

ROGER RHOADES (U. S. Bureau of Reclamation, Denver, Colorado)--1. Studies of ground-water conditions in the vicinity of Coulee City, Washington, were continued for the purpose of determining possible seepage losses from the proposed equalizing reservoir and potential points for recapture of any losses which may occur. 2. A cooperative study with the Geological Survey in central Arizona is aimed at a determination of the safe yield of the aquifers in that area when used in conjunction with surface waters for irrigation. 3. Ground-water studies have been continued in the Central Valley of California, both independently and in cooperation with other agencies, for the purpose of aiding in the plan of distribution of the irrigation water to be made available as this project develops. 4. A number of studies have been made and are continuing relative to ground-water conditions at various dam, reservoir, and canal sites to obtain information necessary for the design and construction of appropriate structures. (See also statement regarding Colorado at end of report.)

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[a] POLAND, J. F., PIPER, A. M., and others, Geologic features in the coastal zone of the Long Beach - Santa Ana area, California, with particular respect to ground-water conditions, U. S. Geol. Surv., processed report, 327 pp., May 1945.

N. A. ROSE (formerly U. S. Geological Survey, Houston, Texas, now with a firm of consulting engineers at Houston, Texas)--Like other offices of the Division of Ground Water of the United States Geological Survey, this office has found little opportunity to engage in research during the past year. However, WARREN HASTINGS of the Quality of Water Division and I have planned laboratory studies with the hope of developing a more effective technique for interpreting electrical logs. The necessary equipment is just about completed and we hope to start the studies as soon as time is available.

In addition to our regular ground-water work in the Houston district we have had an opportunity to study two very interesting problems during the past year; (1) a temperature survey of ground water in Houston; and (2) the effect of the discharge of gas from a defective gas well into the water-bearing sands north of Houston.

(1) The temperature survey was made in May 1944. Temperature readings at depth intervals of 50 feet were obtained in two unused wells (depths 1,414 and 1,676 feet) with an automatic recording subsurface thermometer of the Humble Oil and Refining Company. Based on a standard of 70°.2 F (mean annual temperature at Houston plus a constant of 1°F) the gradient from an average of the readings taken in the 1,414-foot well is 96.0 feet in depth to one degree increase in temperature and in the 1,676-foot well is 97.4 feet per degree increase. In an effort to correlate the temperature gradients in these wells with those of water discharged from pumped wells, observations were made in 25 discharging wells ranging in depth from 65 to 1,618 feet. Most of the wells have only one section of screen, and in calculating the thermal gradient the middle of the screen was considered to be the point of entry of the water into the well. The average temperature gradient of the 25 wells is 98.0 feet in depth per degree of increase in temperature. Based on these data a geothermal gradient of approximately 97 feet in depth per degree of increase in temperature is considered to be applicable to the water-bearing sands in the Houston district to a depth of 1,700 feet.

(2) The discharge of gas from a defective well in the Bammel gas field, about 15 miles north of Houston, into the water-bearing sands caused a phenomenal rise of water levels in many water wells north and northwest of Houston. The THEIS non-equilibrium formula was used to determine the amount of water that would have been required as recharge to the sands in the "affected zone" at Bammel to produce the rise in water level recorded in an observation well 4.7 miles northeast of the defective well. Computations show that the amount required from December 1, 1942 to November 30, 1944 was about six billion gallons of water, or about 14 billion cubic feet of gas at a pressure of 250 pounds per square inch. On November 19 and 20, 1944 the defective well was effectively sealed by the pumping of about 11,000 sacks of cement into the nearby directional well. Since then little or no gas has been discharged into the water-bearing sands and the water levels in the "affected wells" have gradually declined; however, they have not yet reached their normal levels. A paper entitled "Relation of phenomenal rise of water levels to a defective gas well, Harris County, Texas" was published in Volume 29 of the American Association of Petroleum Geologists Bulletin in March 1945.

With respect to the suggestion that the Committee select a subject for a symposium, I believe the subject that is of the greatest interest to most ground-water men is the one suggested by Messrs. THEIS and PIPER in the 1943 report--a review and study of the methods available for estimating ground-water supplies.

I have not been able to find anything new in the way of ground-water research by the oil companies. It seems that most of the companies are still carrying on the activities mentioned in the 1943 report and that new research along this line is being deferred until after the war.

Comment by the Chairman--Now that the war is over it is hoped that it will be possible to arrange a symposium on a review and study of the methods available for estimating ground-water supplies, as originally suggested by THEIS and PIPER and reiterated above by ROSE.

MAX SUTER (Illinois State Water Survey Division, Urbana, Illinois)--Ground-water studies are being continued by the Illinois State Water Survey in the Chicago-Joliet, Peoria-Pekin, and

East St. Louis areas; special field tests are being continued in cooperation with the Soil Conservation Service to measure on eight watersheds rainfall, runoff, soil humidity, and ground-water level in order to follow infiltrations to the ground water; and preliminary studies also have been made in some other areas in the State. The results of these and other studies, including permeability tests on graded sands, are largely unpublished, but some information is included in a report by the State on the influence of floods on ground water, which is appended to a report by the United States Geological Survey on the flood of 1943 [Illinois Department of Public Works and Buildings, Division of Waterways]. There are also elaborate plans for the construction of a hydrologic laboratory and with a comprehensive list of proposed research projects in ground-water hydrology.

Comments by the Chairman--In SUTER'S last letter he reiterated the thoughts expressed in the last three paragraphs of his statement in the report of the Committee in 1944 [Trans. Amer. Geophys. Union, v. 25, part V, p. 716, 1944] and indicated that he would like to hear from other investigators, particularly in regard to ground-water levels near streams that are below stream level. He also stated that attention of universities and colleges should be directed to the importance of ground water and the merit of training engineers thoroughly, mainly in graduate courses, in the properties and behavior of ground water. He also stated, "According to Engineering News Record of January 18, 1945, p. 14, New York University made a laudable start in this direction by opening a course on Ground-Water Hydrology by R. M. LEGGETTE. TOLMAN'S book might be used as a text book, although it stresses the geological aspects too much and is very short in the engineering and hydraulic phases."

Last spring the Chairman had a nice visit with L. K. WENZEL and his family at their home in Bethesda, Maryland, and found that he seemed to be making substantial recovery from the illness which has kept him from active work since the spring of 1944. It is sincerely hoped that WENZEL will soon be recovered sufficiently to resume his work with the Geological Survey and again take an active part as a member of this Committee.

F. WILLIAM GREVE (Hydraulic Engineering Department, Purdue University, West Lafayette, Indiana)--The Engineering Experiment Station of Purdue University has recently initiated a project, entitled "Research on Ground-Water Conservation." The studies included in the project are: 1. Quantitative determination of underground storage; 2. Annual natural recharge of underground storage; 3. Porosity and transmissibility of underground water; 4. Artificial recharge of underground storage; and 5. Variation of the water table. The investigation will be limited in scope to an area of approximately seven-mile radius centered on Purdue University. Cooperating with Purdue University in the project are the Indiana Department of Conservation and the United States Geological Survey.

H. C. BARKSDALE (U. S. Geological Survey, Trenton, New Jersey)--We have very little time for research these days, but are making a study of the recharging of ground-water aquifers in New Jersey by various forms of water spreading. As far as possible, we are also continuing our study of the advance of salt water into certain aquifers that we know are being contaminated.

M. L. BRASHEARS, Jr. (U. S. Geological Survey, Jamaica, New York)--Because of extra work for the armed forces and reduced personnel, no fundamental research was performed at Jamaica during 1944. However, one or two of our projects may be of general interest. During the year two reports, one relating to hydrology and the other to geology, were prepared. The report by C. E. JACOB entitled "The Water Table in the Western and Central Parts of Long Island, New York" includes a map showing the contours of the water table and several profile drawings showing the shape of the water table in a number of places on Long Island. JACOB has compared the configuration of the water table as shown by his map with similar maps, some of which were prepared as long ago as 1903, and has pointed out a number of interesting features. It is indicated also that excessive pumping in Brooklyn, at the westernmost end of the Island, has drawn the water table below sea level over large areas, whereas in the other parts of Long Island there has been no great lowering of the water table even though heavy pumping has been carried on for a number of years. The other report entitled "The Configuration of the Bedrock Surface in the Western Part of Long Island, New York," by M. L. BRASHEARS, Jr., contains a map which shows the position of the bedrock with respect to the land surface. As all of the highly permeable water-bearing sands on Long Island lie above the old bedrock surface the map will aid well drillers as it will show the maximum depth to which productive drilling may be carried. Further, one of the most extensive artesian formations on Long Island, the Lloyd sand, lies just above the old bedrock surface and its position with respect to land surface can therefore be deduced from the bedrock map. It is expected that the reports of JACOB and BRASHEARS will be published sometime during 1945.

During 1944 ground-water studies were begun in Rhode Island in cooperation with the State Industrial Commission. Until the beginning of this program no organized investigations of the ground-water resources of Rhode Island had been performed and very little information concerning these resources appears in any literature. Work was begun in Providence where the largest withdrawals in the State occur and it is expected that a preliminary report on conditions in that City will appear during 1945.

D. J. CEDERSTROM (U. S. Geological Survey, Charlottesville, Virginia)--Perhaps one should not list foraminiferal studies under the heading of research on ground-water hydrology but we have done a great deal of work along that line with considerable success. Some of the broad phases of geology have been radically altered and, naturally, some very new ideas about the occurrence of ground waters have been brought forth by these results.

Comments by the Chairman--An investigation of the Roanoke, Virginia, area was recently completed by B. F. LATTA, who was assigned from Lawrence, Kansas, while CEDERSTROM was working on military ground-water supplies in the Pacific.

JACK B. GRAHAM (U. S. Geological Survey, Philadelphia, Pennsylvania)--In Pennsylvania the Geological Survey is continuing to cooperate closely with CARROLL F. MERRIAM of the Pennsylvania Water and Power Company in his studies of predicting low stream flow of the Susquehanna River from observation-well records obtained by the Survey, and plans to include a graph of MERRIAM'S Susquehanna Basin index in the 1944 water-level report. It is the plan to try MERRIAM'S method on the records for other basins in Pennsylvania. [See also statement below by MERRIAM.]

A. L. GREENLEE (formerly U. S. Geological Survey, Grand Forks, North Dakota)--Current ground-water work in North Dakota has included determinations of transmissibility, specific yield, recharge, and storage in the Souris River Valley at Minot, North Dakota, in the Big Sioux Valley at Sioux Falls, South Dakota; in the James River Valley at Jamestown, North Dakota; and of the Fort Union formation at Dickinson, North Dakota. Other studies pertained to recharge from floods in the Red River Valley-Lake Agassiz silts, at Fargo, North Dakota; to the overdevelopment of local sand lenses in glacial drift at Fessenden, North Dakota; to recharge and discharge of ground water in the vicinity of the Army Engineer's control dam on the upper Mississippi at Lake Winnibigoshish, Deer River, Minnesota; to control measures as applied to the artesian flows from the Dakota sandstone in North Dakota; and a study has begun of the local unwatering of the artesian supply in the Fox Hills sandstone in the Bowman area, North Dakota.

W. F. GUYTON (U. S. Geological Survey, Louisville, Kentucky)--Investigations are continuing in the Louisville, Kentucky, area in order to relieve a serious shortage of water and especially to provide adequate supplies for war industries. It was determined that during 1944 recharge to the ground-water reservoir at Louisville was only about 40 million gallons a day whereas the pumpage exceeded this amount by nearly 20 million gallons a day. Through an intensive study involving test drilling, test pumping, measurement of water levels and temperatures in many observation wells, experiments to recharge the aquifer using both surplus treated city water in winter and heated ground water that had been used for cooling, and consideration of other conservation measures, it is expected that pumpage soon should be reduced to an amount which probably does not exceed the natural recharge. The program has been described in several publications by GUYTON and others listed in Appendix E and is referred to in the statement in this report by MEINZER. The investigation is continuing in order to refine the estimates, effect a better distribution of pumping, and to explore undeveloped areas.

R. M. JEFFORDS (formerly U. S. Geological Survey, Morgantown, West Virginia)--Most of the work of the United States Geological Survey in this area during the year has related to recharge from rivers--its occurrence, determination, and effects--at numerous points along the Ohio River [see report by JEFFORDS listed in Appendix E]. Special attention has been given to the determination of recharge from the river by interpretation of quality of water data, thus:

The Ohio River contains water that differs markedly from that in the alluvial water-bearing strata receiving recharge from local precipitation only. As river water moves into the aquifer (at differing rates depending upon river stage, pumpage, and temperature) the character of the water pumped from the wells changes. Accordingly, relatively large changes in temperature, hardness, alkalinity, and sulfate indicate that some of the water is being obtained from the river. Inasmuch as the percentage of equivalents of sulfate increases and the percentage of equivalents of bicarbonate decreases as the quantity of river water increases, it is possible to determine the approximate percentage of river water in the water pumped from the well.

This method, using partial analyses, should have relatively wide application along the Ohio River Valley in rapid or reconnaissance studies, or at locations where pumping tests are impracticable. In more detailed investigations, these data should be useful also in the proper interpretation of the basic pumping test data.

P. H. JONES (U. S. Geological Survey, Baton Rouge, Louisiana)--During 1944 the principal effort of the Louisiana office was concentrated in the Baton Rouge area, in which serious declines of water levels in wells had resulted from accelerated and continuous pumping of closely-spaced industrial wells. Well inventories, including all available data on the physical characteristics of about 400 wells ranging in depth from about 35 to 2,610 feet, along with pumping rates and drawdown, were completed. The inventory included 151 industrial wells in use or abandoned. Pumpage inventories were begun and have been continued. Water-level fluctuations were carefully recorded by strategically located observation wells equipped with automatic recorders. Pumping tests were conducted to determine transmissibility and storage of the cooling-water sands less than 1,200 feet below the land surface in the industrial district. A report including three maps showing well locations and lines of cross sections, and two hydrographs (one showing pumpage plotted against observed water levels) has been transmitted to the Washington office.

The exploratory program in the Natchitoches area was completed in 1944 and the report written and released for publication [see papers by J. C. MAHER and P. H. JONES, and by T. B. STANLEY, Jr. and J. C. MAHER listed in Appendix E]. A new and entirely untouched source of ground water was discovered and is at present supplying about 250,000 gallons of water a day to the city of Natchitoches. The quality of the water is excellent and the aquifer can easily supply more water as the demands increase.

A test-drilling program for the town of Colfax was begun in 1944. The third test well, drilled in August, penetrated a brackish-water sand which has been proven to yield fresh water up-dip. Two test wells, located about one mile up-dip, were drilled in March of this year. Forty feet of sand yielding soft, fresh water was discovered at a depth of about 175 feet. Plans for the development of this supply, which is about four miles from Colfax, are under way.

Piezometric maps showing ground-water conditions in the Pleistocene gravel beds of southwestern Louisiana, which are drawn upon for rice irrigation, were expanded in 1944 to take in all or parts of ten parishes. These maps indicate that considerable recharge is occurring from the east in an area that had not been considered important in this respect prior to the new work.

R. G. KAZMANN (formerly U. S. Geological Survey, Memphis, Tennessee)--The investigation of ground-water supplies in Memphis expanded its scope in the past year after the preparation of a typewritten report summarizing the available information on the water supply of the Memphis area. In the spring of 1945 an extensive series of pumping tests was made on the deepest sand in the area, about 1,400 feet below the surface and about 1,200 feet below sea level. The tests were successful and storage coefficients and transmissibility coefficients have been computed. These will enable short-term (one or two years) predictions of water levels in wells tapping this sand, assuming certain pumping rates. Long-range predictions of water level will be possible only after the geology of the aquifer has been studied in detail and the outcrop area is known.

JOHN KAMMERER of the Memphis office has set up a laboratory for the study of sediments. With regard to ground-water investigations started in previous years, data are now available to show the effect of temperature changes on the yield of wells tapping an aquifer recharged by a nearby river. Data from the West Virginia Ordnance Works bears out the theory of viscosity effects, unmistakably. A 30 per cent change in yield has been found in some wells due to temperature changes in the aquifer.

RUSSELL M. JEFFORDS and I are now preparing a paper on recharge which will discuss the importance of recharge and give several methods for determining whether or not a given place on a river bank will obtain recharge. Among the methods outlined are extensions of pumping-test methods and geochemical methods which have been newly applied by JEFFORDS from his extensive study of data obtained by waterworks operators in his territory.

CARROLL F. MERRIAM (Pennsylvania Water and Power Company, Baltimore, Maryland)--We are continuing analysis of ground-water levels and stream flow for assistance in forecasting stream flow in the low-flow seasons. A paper entitled "Natural fluctuations of ground water and interpretation in terms of river flow" was presented in the spring of 1945 at the meeting of the Four States Water Works Association in Philadelphia. This paper was published in the Journal of the American Water Works Association, v. 37, pp. 632-637, July 1945.

GARALD G. PARKER (U. S. Geological Survey, Miami, Florida)--Intensive investigations of ground-water conditions are being made currently in several areas of southern Florida. Among these the most important are: Greater Miami, Fort Myers, Lake Worth, and Fort Pierce. The problems involve chiefly safe yields of formations and salt-water encroachment. Until this office was opened in 1939 little research had actually been done on the water resources of southern Florida, and even today knowledge in many parts of the area is fragmentary.

Work is proceeding along two main courses: (1) Intensive local investigations with the object of finding a solution to a pressing water-supply problem; and (2) systematic investigations looking toward the establishment of long-term records, especially on salt-water encroachment, and changes in water level and artesian pressure. Two current reports by PARKER and others are listed in Appendix E, and several additional reports are in press.

T. W. ROBINSON, (U. S. Geological Survey; formerly Safford, Arizona, now Carson City, Nevada)--The intensive investigation of the lower Safford Valley, Arizona, has been completed and the report was transmitted to Washington in January 1945. This investigation, which dealt primarily with the determination of the use of ground water by natural vegetation proceeded along four main lines of attack:

1. A method for relating the drainage of unconsolidated soil samples in the laboratory to specific yield. It is based on the relationship between the percent of drainage of a sample in the laboratory at the end of a 48-hour period to the specific yield of the sample material. This relationship was established by determining the percent of drainage at the end of 48 hours and the specific yield and then developing a relationship curve from these data. Once the curve for a particular size range is developed, the specific yield of material in the particular size range may be determined by referring the percent drainage in 48 hours to the curve. Thus far the relationship curve has been developed for only one size range, medium sand. Further tests, however, are in progress for other size ranges of fine and coarse sand and for gravel.

The apparatus used was adopted from the variable-head permeameter originally devised and used by C. V. THEIS. The apparatus was redesigned for larger manometer and permeameter tubes. Drainage is accomplished by means of a wick inserted into the sample after it has been saturated and after the permeameter or sample holding tube has been removed from the apparatus. The procedure has been adopted so that porosity, specific gravity, and apparent specific gravity may also be computed from the data obtained during the test.

2. Tank experiments for determining the use of water by phreatophytes and loss by soil evaporation. For these studies 29 sunken tanks filled with soil were used. In 12 of the tanks the soil was left unplanted, so that the rate and effect of evaporation from bare soil surfaces could be studied; in the remaining 17 tanks the soil was planted with phreatophytes common to the Safford Valley--salt cedar (*Tamarix gallica*), batamote (*Baccharis glutinosa*) and cottonwood (*Populus fremontii*)--in order to determine variations and amounts of water involved in evapo-transpiration when water levels are maintained at depths of two, four, six, and eight feet below the land surface.

3. The conception and application of the volume-density theory which was developed for evaluating plant growth in terms of water use. The theory based on experiments holds that the amount of water transpired by phreatophytes varies directly as the volume of frondage or weight of fronds for a given depth to the water table. It provides a standard method for properly translating the results of experiments on the use of water by phreatophytes either by the tank method or the method based on diurnal fluctuations of the water table, into the depth of water transpired under natural field conditions. The theory takes into consideration the density of growth of the plants and density of fronds on the plants, thickness or vertical depth of fronds in the experimental tank or plot and in the field under natural conditions.

4. A program of observations of the diurnal fluctuations of the water table in areas of phreatophytes to determine the use of water by them and a study of the relative effects of humidity on the rate of transpiration. The rate of transpiration is greater when the humidity is low than when it is high.

A series of experiments on phreatophytes grown in tanks demonstrated that the rate of transpiration at night is appreciable for certain species of phreatophytes and cannot be neglected when computing the amount of water transpired by the equation $q = y(24 \pm s)$ originally developed by WHITE. Because of the effect of transpiration at night, the equation was modified by the introduction of a constant k as follows $q = yk(24 \pm s)$. Values of k determined for the phreatophytes under observation were: For salt cedar 1.25; for baccharis 1.07; and for cottonwood 1.00.

E. J. SCHAEFER (U. S. Geological Survey, Columbus, Ohio)--The investigation in the Mill Creek Valley and Miami Valleys immediately north of Cincinnati was continued throughout 1944 in cooperation with the Commissioners of Butler and Hamilton Counties and the Federal Works Agency. Because of the War a permanent solution to the problem in the Mill Creek Valley has not been possible. However, conservation measures adopted to insure adequate cold water for war industries in the summer months have proven effective. Construction of a well field immediately south of Hamilton to supply the plant of the Wright Aeronautical Corporation at Lockland has resulted in a considerable reduction of pumping in the vicinity of Lockland causing a leveling off of the downward trend of water levels in that area. Similarly, two industries in the area near the north city limits of Cincinnati have resorted to using Cincinnati water (taken from the Ohio River) in the winter months when it is cold enough for their purposes. As a result the downward trend has been stopped in that area so that these industries will be able to operate next summer with adequate supplies of cold water.

Ground-water investigations throughout the rest of the State consisted mainly of establishing observation-well programs in the heavily pumped areas to build up basic data regarding conditions in those areas.

H. A. WAITE (U. S. Geological Survey, Lincoln, Nebraska)--Ground-water investigations in Nebraska in 1944 centered around test-drilling programs in several parts of the State. Three reports listed in Appendix E, one by E. C. REED and two by WAITE and others, give the results of several studies and drilling programs. In addition considerable test drilling was done in areas of southeastern Nebraska underlain by glacial deposits, including the tracing of the buried valley of the pre-glacial Republican River, and at several proposed reservoir sites in the Loup River Basin.

Maps are now being prepared of southeastern Nebraska showing the locations of all test holes that have been drilled, the configuration of the water table by means of contours, the configuration of the underlying bedrock surface by means of contours, and the approximate thickness of saturated water-bearing material by means of isopachs constructed on the basis of test-hole information.

Comments by the Chairman--Current ground-water investigations in Kansas by the State and Federal Geological Surveys (now under the supervision of V. C. FISHEL) included the completion of reports on Kiowa County, Grant, Haskell, and Stevens Counties, Seward County, Thomas County, Republic County and northern Cloud County, the Kansas City area, Kansas, and an area in Russell County; the completion of field work in Barton and Stafford Counties, Pawnee and Edwards Counties, and the Wichita area; and the beginning of field work in Kingman County, Rice County, Norton County, and in the Hutchinson, Medicine Lodge, and Kirwin areas. A report by LATTA is listed in Appendix E.

A new cooperative ground-water program in Colorado was begun in July 1945 by the Geological Survey and the Colorado Water Conservation Board, under the supervision of the Chairman. Initial projects under way include an investigation of the geology and ground-water resources of the Big Sandy Creek Valley above Limon, with special reference to irrigation from wells; a detailed investigation of the ground-water conditions along a proposed sub-drain to be constructed by the Bureau of Reclamation in the San Luis Valley; and a study of the artesian basin in the vicinity of Grand Junction.

U. S. Geological Survey,
Denver, Colorado.

(Manuscript received January 14, 1946; presented by title at the Twenty-Sixth Annual Meeting, Washington, D. C., June 1, 1945; open for formal discussion until September 1, 1946.)

APPENDIX A--REPORT OF THE SUBCOMMITTEE ON PERMEABILITY

C. E. Jacob, Acting Chairman

The Subcommittee on Permeability of the Permanent Research Committee on Ground Water of the Section of Hydrology, was organized in 1943 to provide for the open discussion of the terminology relating to permeability with a view toward the elimination of conflicting usages and the clarification and standardization of acceptable terms. Confusion had arisen not only in the units of measurement but also in the notation and nomenclature of permeability. It seemed desirable to have general agreement particularly in regard to the names of the different physical parameters in common use and their symbols.

The membership of the Subcommittee is as follows:

L. K. Wenzel, U. S. Geological Survey, Washington, D. C., Chairman

B. A. Bakhmeteff, Columbia University, New York, New York
W. A. Bruce, Carter Oil Company, Tulsa, Oklahoma
S. E. Buckley, Humble Oil and Refining Company, Houston, Texas
V. C. Fishel, U. S. Geological Survey, Lawrence, Kansas
Loranus P. Hatch, Army Industrial Hygiene Laboratory, Baltimore, Maryland
M. King Hubbert, Shell Oil Company, Houston, Texas
O. W. Israelsen, Utah Agricultural Experiment Station, Logan, Utah
C. E. Jacob, U. S. Geological Survey, Washington, D. C.
W. C. Krumbein, Gulf Research and Development Company, Pittsburgh, Pennsylvania
W. B. Langbein, U. S. Geological Survey, Washington, D. C.
O. E. Meinzer, U. S. Geological Survey, Washington, D. C.
Morris Muskat, Gulf Research and Development Company, Pittsburgh, Pennsylvania
L. A. Richards, U. S. Regional Salinity Laboratory, Riverside, California

Discussions by this Subcommittee were initiated by a questionnaire sent to the members by Chairman L. K. WENZEL in December 1943. He raised the following questions:

(1) Should the coefficient of permeability depend only on the structure of the material, or should some other name be used to express this property in view of the fact that, as now generally used, the coefficient of permeability is not independent of properties of the fluid or the combined properties of the fluid and the material?

(2) Should a name be coined, or is there a suitable one in existence, for expressing the combined properties of the material and fluid for practical application in one local area?

(3) What are the parameters that should be included in the equation of flow of fluids that relate only to the structure of the material?

In the Transactions of 1944 [v. 25, Part V, pp. 721-22], a brief progress report was given by former Acting Chairman W. B. LANGBEIN in which reference was made to WENZEL'S memorandum and to the replies that had been received from members of the Subcommittee up until that time. Replies from thirteen of the members are published herewith, three of them in the form of separate papers as Appendices B, C and D of this report.

It is noted that although there is a healthful diversity of viewpoint among the several members of the Subcommittee there is now general agreement regarding questions (1) and (3). All members of the Subcommittee have replied in the affirmative to the first part of question (1), though two of them favor eliminating the fluid properties, density and viscosity, by correcting to a standard fluid at specified conditions of temperature and pressure rather than by giving them explicit expression in the fundamental flow equation.

Question (3) was interpreted variously by different members of the Subcommittee. (Unfortunately, through inadvertance the word "permeameter" appeared in place of the word "parameter" in the questionnaire as originally sent out.) Nevertheless, the replies to this question indicate that the parameters constituting permeability, which relate only to the structure of the material, are (1) a characteristic length (in clastic materials preferably the mean-grain diameter) typifying the size of the openings through which the flow takes place, and (2) a constant relating to the porosity and to the arrangement and size-distribution of those openings. Thus a preference is indicated for expressing permeability as the product of this nondimensional constant and the square of the characteristic length, with the dimension L^2. If that is done, the acceleration of gravity and the viscosity and density of the fluid, or ratios of alternative combinations of these, will appear explicitly in the equation expressing DARCY'S law.

In regard to question (2) it will be noted that several suggestions have been offered. Various combinations of the acceleration of gravity, the viscosity and the density of the fluid, and the permeability of the medium have been suggested for practical application in those fields where a single fluid is involved. The most common is one involving all four of these factors, k, having the dimensions L/T. It was first termed in English "transmission constant," by SLICHTER, and has more recently been called "transmission coefficient," "DARCY'S coefficient," "coefficient of permeability," or simply "permeability." Another name, which has been suggested by a member of the Subcommittee, is "permeation factor."

In dealing with the special case of the flow of water or of oil in the plane of bedding of a uniformly thick bed or geologic stratum, it has been found convenient to combine in a product the coefficient mentioned just previously and the thickness of the bed to obtain a measure of the overall ability of the bed to transmit the particular fluid in question. This combined factor was named "coefficient of transmissibility" by THEIS in 1935. It has the dimensions L^2/T and is commonly symbolized by T. Some members of the Subcommittee have suggested that the need expressed in question (2) is met by the "coefficient of transmissibility."

Another combination of the properties of the fluid and medium that has been proposed, particularly for use in soil-moisture studies, is expressed by the ratio of the permeability L^2 to the kinematic viscosity L^2/T. It has simply the dimension of time, and has been designated variously as "specific conductivity," "conductivity," or "transmission function."

It should be pointed out that, in dealing with the flow of a single fluid of constant density and constant viscosity in a homogeneous medium, at least three alternative forms of DARCY'S equation are permissible. In the first the resistance to flow may be expressed by the ratio of the viscosity to the "permeability" L^2 and the driving force may be expressed in terms of the piezometric pressure, whose gradient gives the force per unit volume of fluid. In the second the resistance to flow may be expressed by the reciprocal of the so-called "transmission constant" L/T and the driving force by the head (sum of pressure head and elevation), whose gradient gives the force per unit weight of fluid. In the third the resistance is given by the reciprocal of the "conductivity" T and the driving force by a potential whose gradient gives the force per unit mass. In one field of study one method of expression may be found most convenient; in another field, another method. Workers in the different fields should be allowed to exercise their preference, although the need for a common denominator for intercomparison should be obvious to all.

Viscous fluids that permeate porous solids are analogous to certain other "fluids" that are conducted or transmitted by solids, such as electricity or heat. The following parallel expressions may be helpful in clarifying the terminology connected with those phenomena: (a) In the process of conduction, a conductive solid conducts a conductible fluid; the solid manifests conductivity and the fluid manifests conductibility. (b) In the process of transmission, a transmissive solid transmits a transmissible (or transmittable) fluid; the solid manifests transmissivity and the fluid manifests transmissibility. (c) In the process of permeation, a permeative fluid permeates a permeable solid; the fluid manifests "permeativity" and the solid manifests permeability.

We speak of the conduction of electricity and the conduction of heat. As there is only one "electrical fluid" and only one "thermal fluid" the verb "conduct" together with the several modifying suffixes is adequate to designate the properties relating to those phenomena. In permeation, however, we have a great variety of fluids and accordingly it has been found necessary to employ other root words to designate the several properties, singly or in combination. There is an obvious advantage to words such as "conduct," "transmit," and "permeate" that are readily susceptible of modification by the addition of suffixes. These have been used by different writers to describe the same phenomenon. It would seem desirable, however, to have general agreement as to which of these or other root words is to apply to the coefficient in each of the three alternative forms of DARCY'S law.

If the word "permeability" is to be reserved for that characteristic L^2 of the medium which refers solely to the geometry of its porous structure, there remain to be found acceptable terms for the other two coefficients in common use. With regard to the second, which is the coefficient in DARCY'S original equation, it should be pointed out that strenuous objections have been raised to SLICHTER'S name "transmission constant," the point being made that it is not a constant but rather a function of several variable factors. This coefficient is quite widely known also as the "transmission coefficient." In physics, in the theory of transmission and absorption of radiation at an interface between two media, the terms "transmission coefficient" and "transmissivity" are used synonymously. (See WELD, Glossary of Physics, McGraw-Hill, 1937.) Perhaps that terminology might be borrowed for use in permeation. Then DARCY'S coefficient could be called "transmissivity" and one could speak of a medium as being more or less transmissive with respect to one fluid or another. On the other hand, however, it may eventually be decided advisable to stick to one root and to designate DARCY'S coefficient by some term such as "permeation factor" or "specific permeation rate," though we would still have the problem of naming the third coefficient in common use.

With regard to THEIS' "coefficient of transmissibility," it would appear that a more appropriate term etymologically would be "coefficient of transmissivity," or simply "transmissivity." The fluid and not the medium is transmissible; the medium is transmissive. If it is considered that the word "transmissivity" is preempted through the parallel use of the related word "transmissibility," then it will be necessary to use some other name for DARCY'S coefficient. Otherwise DARCY'S coefficient might be called "transmissivity" and THEIS'S coefficient some name such as "stratal transmissivity" or "planar transmissivity," the latter coefficient being the product of the former and the thickness of the transmissive stratum.

The foregoing are merely suggestions as to how present difficulties of nomenclature might be resolved. This matter will be considered further by the Subcommittee.

The writer wishes to express his appreciation to the members of the Subcommittee, whose responsive participation has made the temporary chairmanship an enjoyable duty. It is felt that in certain fields, such as petroleum and ground water, the Subcommittee has adequate representation, at least in this country. However, in other fields, such as soil mechanics, soil physics, ceramics, and textiles, a wider representation would be desirable. It is recommended, therefore, that the membership of the Subcommittee be enlarged to include workers in those fields, not only in the United States but in countries abroad as well. Only in that way will the work of this body become recognized as representative of the thinking of those whose common meeting ground is fluid permeation.

BORIS A. BAKHMETEFF (Columbia University, New York, New York)--In answer to the questions set forth in the memorandum of December 2, 1943, relating to the Subcommittee on Permeability, I take pleasure in submitting the following:

For all practical purposes, it will be sufficient to deal with underground flow within the customary DARCY premises of linear resistance, setting

$$Q = AKi \quad \ldots\ldots (1)$$

with Q the volume of fluid permeating in unit time across the area A under a piezometric gradient i, and with K a quantity referred to at times as the "permeability coefficient" or simply "permeability," and called by other authors the "transmission constant."

Within the precincts of the DARCY law, the structure of K is known to be

$$K = (g/\nu)\delta^2 f(\alpha) = [\gamma/\mu][\delta^2 f(\alpha)]. \quad \ldots\ldots (2)$$

with δ the particle size, μ and ν respectively, the dynamic and the kinematic viscosity of the fluid, γ the specific weight of the fluid, and α the volumetric porosity of the bed. The overall process of underground flow depends thus on two constituent parametric groups. One, exemplifying the physical properties of the fluid and equaling μ/γ, or the viscosity per unit weight. The other, characterizing the geometry of the porous bed and featured by

$$\delta^2 f(\alpha) \quad \ldots\ldots (3)$$

with $f(\alpha)$ a "porosity function." The latter is a dimensionless expression formed out of the porosity factor α, and appraising the faculty of a porous structure to pass fluid.

As matters stand, the profession is not unanimous in defining the particular form for $f(\alpha)$. In fact, KOZENY, FAIR, and HATCH and others make $f(\alpha) = (1/179)\alpha^3/(1-\alpha)^2$ whereas BAKHMETEFF and FEODOROFF [Trans. Amer. Geophys. Union, v. 24, no. II, p. 545, 1943] prefer setting $f(\alpha) = \alpha^{4/3}/320$. The pertinent feature, however, is that the porosity function is taken to constitute an algebraic group, built out of the α quantity, with a multiplier in the form of a numerical constant to be derived from experiment.

The aforesaid considerations should furnish the necessary physical basis for a comprehensive terminology to be used in connection with flow through porous materials. The wording, on the other hand, should be selected so as to conform to the meaning which the English language attributes to this or that expression.

Thus the noun "permeability" is defined by the dictionary as the "state or quality of being permeable." The adjective "permeable" qualifies in turn "something that may be passed through." The lexicographic term for the process of motion is the noun "permeation," defined by the dictionary as "the act of permeating," and the verb "to permeate," given as meaning "to penetrate and pass through the pores or interstices of . . ."

In this light, "permeability" is obviously the faculty of porous media to allow "permeation." Accordingly, with reference to equation (2), the term "permeability" should relate to the group $\delta^2 f(\alpha)$ only, qualifying the extent to which a porous structure is "permeable." The overall process of flow should be described as "permeation." Water, oil, gases, and other fluids *permeate* through a porous bed at the rate determined by the overall equation (2). The K quantity accordingly measures the intensity of permeation, conditioned by the combined action of bed geometry and the physical properties of the fluid. An appropriate term for K would be "*permeation factor*."

The memorandum refers to two possibly conflicting view-points, the "theoretical" and the "field." There is no real reason for such conflict, nor should there be any antithesis between theory and practice. Indeed, theory, whenever abstract or inconsiderate of reality, is *ipso facto* sterile and futile, just as practice which tends to operate outside of a rational framework based on physical and dynamical precepts, is necessarily blind and fruitless.

An important feature, which cannot be over-emphasized in this connection, is that both theory and practice should invariably use a consistent system of units, and moreover should make a practice of using definitions, comprehensively formulated in general terms, independent of units of measurement. A good illustration is the manner of comprehensively defining the overall permeation factor K in equation (1). The latter, formally, has the dimension of a velocity. The rational way, nevertheless, directly related to the field practice of characterizing an aquifer as mentioned in the memorandum, should be to define the permeation factor as

$$K = [L^3/L^2T] = (Q/Ai) = \text{(volume of flow)/(area x time x piez. gradient)} \quad . \; . \; . \; . \; . \; (4)$$

In the customary engineering units the numerical value of K would be: The volume of flow in cubic feet per second, across a square foot, under a unit gradient. Such a basic unit may easily be adapted to any desired field requirements; thus:

$$\text{K in gallons per ft}^2\text{, per day} = 7.48 \times 86400\,\text{K in ft}^3\text{, per ft}^2\text{, per sec}$$

In addition to using the foot and second, the engineer habitually expresses "ponderosity" in terms of "force", using the *pound-weight* as his unit, in contrast to the "*pound-mass*" of the physicist.

Consistent practice in adhering to the pound (force), foot, and second system would eliminate, for example, a great deal of the bewildering confusion which prevails in engineering circles in regard to expressing numerically the dynamic viscosity μ. The practical way would be to abstain from the different conventional scales and to measure viscosity in terms of lb. sec./ft^2. (For numerical figures see GIBSON, Hydraulics, p. 15; ROUSE, Fluid Mechanics for Hydraulic Engineers, p. 417, and others.)

W. A. BRUCE (Carter Oil Company, Tulsa, Oklahoma)--I agree with KRUMBEIN, MUSKAT, MEINZER, JACOB, and others, that a coefficient of permeability should be such that it refers to the shape of the channels in the rock or porous media through which the fluid is flowing, and that this coefficient should not refer to the properties of the fluid flowing, that is, the coefficient should have the dimensions of L^2.

I also agree with MEINZER and others that practical coefficients of transmissibility are useful and that these coefficients should be familiar to workers in allied fields.

L. A. RICHARDS expressed a point of view which may be pessimistic, but it is probably true that we cannot hope to have a universally used coefficient of permeability. The next best thing is to have a recognized standard coefficient of permeability which could be used by authors who were willing to express their results both in the practical unit of their field and the standard unit.

In regard to drawing close comparisons between data on the flow of fluids through porous media obtained in different fields of study, it is my belief that the science of flow through porous media is still too immature to permit the transfer of existing laboratory data on rock cores by the conventional air-permeability method to the transmissibility of various liquids and gases through subterranean aquifers. Probably the most difficult situation to overcome, regarding the comparison of laboratory and field data, results from the change in the properties of rock when it is removed from its natural environment to the laboratory. For example, the mere action of drying the rock fragment is such to change some permeabilities a thousandfold. Obviously, comparison in such cases would be impossible and permeabilities determined on the dry rock fragment would be completely misleading as to the transmissibility of the water through the aquifer.

S. E. BUCKLEY (Humble Oil and Refining Company, Houston, Texas)--With regard to the various questions raised, I am rather in accord with what seems to be the consensus of the replies. I believe that it is highly desirable to have a permeability unit or units which deal solely with the properties of the solid medium through which the fluids pass. I recognize that for particular industries it may be desirable also to have a combination factor which includes the properties of the fluid as well as the medium. I can see the advantage of such a factor for use in ground-water studies or in ceramics. In the oil business, since we must deal with oil, gas, and water of different viscosities and densities, we are forced to use a permeability factor which is related solely to the porous medium and to bring in the properties of the flowing liquid or gas separately. However, in order that we may compare the physical properties of the materials dealt with in various industries, I think that it is essential that in all technical papers dealing with fluid flow the units used be specifically stated in the paper. Provided the units are stated, then it is rather immaterial whether the author uses a combination factor or separate factors and rather immaterial whether the units used are English units, cgs units, or a combination.

In many of our problems dealing with the control of oil fields we are forced to study the aquifers from which the oil fields derive their water drive. There is, therefore, a very close tie between ground-water studies and oil-reservoir studies. Both the permeability and the specific yield are very important in this connection. In order that the petroleum reservoir engineers may derive the maximum benefit of the work of the hydrologists, it may be desirable to agree on some satisfactory unit for permeability of the solid medium which could be used by both groups. However, even here, if all authors are careful to designate the unit employed, there should be no confusion.

With regard to the use of the phrase "coefficient of permeability," I believe that the term "coefficient" is superfluous.

I also feel that in those industries where a combination factor is used which includes the permeability of the solid medium as well as the properties of the fluid, some term other than permeability should be used for the combination factor.

LORANUS P. HATCH (Capt., Sanitary Corps., Army Industrial Hygiene Laboratory, Baltimore, Maryland)--With regard to question No. 1, a permeability factor may be used to define either the structure of the material, or the ability of the material to transmit a fluid under standard conditions. But these two measures of the coefficient should not be combined in any way. The structure of the material, as in pipe flow, can be expressed in terms of the size of the flow channels through the material.

The transmission capacity is well defined by the equation, $P = Q/MI$ together with a temperature factor when

P = Coefficient of permeability
Q = Volume of fluid per unit time
M = Gross area normal to flow
I = Hydraulic gradient

Any determination of the permeability factor from the structure of the material should be made in accordance with a rational equation of flow. The following equation is the one most familiar to the writer and will serve for an example.

$$I = (h/\ell) = (k/g)(u/r)(A/V)^2 v(1-a)^2/a^3$$

in which h is resistance head, ℓ is length of flow, k is equation coefficient, g is gravity constant, u is viscosity, r is fluid density, A is surface area of particles, V is solid volume of particles, a is porosity, and v is velocity over gross area, or Q/M.

Now,

$$P = (k/g)(Q/M)(u/r)/I = (V/A)^2 a^3/(1-a)^2$$

$P = (k/g)(Q/M)(u/r)/I$ is based on the properties of the fluid. $P = (V/A)^2 a^3/(1-a)^2$ is based on the properties of the structure.

From the properties of the structure, P is measured by the size characteristic of the flow channels and the porosity, or by $[(V/A)a/(1-a)]^2$ and a. The latter porosity in this case is a measure of the ratio of open area to gross area normal to the flow.

The same reasoning could be applied to flow through a pipe or a group of pipes arranged in parallel.

Therefore, as in pipe flow, the permeability factor should depend wholly on the properties of the flow structure, or wholly on the properties of the fluid. But it should be possible to use them interchangeably, and one may be used as a measure of the other.

Likewise, the size of a pipe could be expressed by its permeability factor as measured by

$$(Q/M)(u/r)/I$$

With regard to question 2, I can see no reason, in a measure of permeability, to combine the properties of the fluid and the material. For a soil structure, the capacity to transmit fluid will depend on the size of the flow channels and the proportion of open area in a given cross section.

With regard to question 3, the parameters that relate only to the structure of the material are those required to determine the characteristic size of flow channels and the relative amount of open area normal to the flow. These are as follows: (1) Measurements of the soil grains to give the surface area of grains per unit of solid volume. This may involve a determination of particle size and size distribution as well as particle shape. (2) A measure of the arrangement of the grains, the homogeneity of the packing, or the degree of stratification. (3) The porosity or ratio of open space to total packed volume.

M. KING HUBBERT (Shell Oil Company, Houston, Texas)--With regard to question 1, in my opinion, the coefficient of permeability should be restricted to the geometrical properties of the medium only, and should be independent of the nature of the fluid.

With regard to question 2, if the unit of permeability is to be defined as a property of the medium only, in any practical and consistent system of units its simplest definition is the unit of length squared. At some later date, it may be desirable to define some practical unit which is a small sub-multiple of the square of one of the standard units of length. For the present, however, the best usage would appear to be to express the permeability in terms of the square of the unit of length employed, say the foot squared or the centimeter squared. The conversion from the unit given to any other can then be simply obtained.

With regard to question 3, the complete equation for the flow of a fluid through a sand is contained in any of the following four equivalent expressions:

$$q_s = (Nd^2\rho/\mu)E_s$$

$$q_s = (Nd^2\rho/\mu)(g_s - \partial p/\rho\partial s)$$

$$q_s = -(Nd^2\rho g/\mu)(\partial h/\partial s)$$

$$q_s = -(Nd^2\rho/\mu)(\partial\phi/\partial s)$$

where q_s is the volume per unit area per unit time, or specific volume discharge, in the direction s, and

$$E_s = g_s - (\partial p/\rho\partial s) = -g(\partial h/\partial s) = -\partial\phi/\partial s$$

is the impelling force per unit of mass of the fluid in the direction s; h is the total head or the height of rise of the fluid above a standard datum in an open-topped manometer terminated at the point of interest, ϕ is the fluid potential or mechanical energy per unit of mass, g_s is the component of gravity in the direction s, and p the pressure at the point of reference. N is a dimensionless factor depending upon the shape of the interstices through which the fluid flows, d is a length parameter which characterizes statistically the fineness or coarseness of the fluid network, ρ is the density of the fluid and μ its dynamic viscosity. The product Nd^2 is the only one that depends upon the sand and therefore constitutes the simplest possible definition and measure of the permeability.

O. W. ISRAELSEN (Utah Agricultural Experiment Station, Logan, Utah)--With regard to question 1, the "permeability" should depend only on the structure of the material, and be understood as independent of the properties of the fluid. No other name should be used to express this property of permeability.

With regard to question 2, the word "conductivity" should be used to express the combined properties of the material and fluid for practical application to field problems of fluid flow in porous media, and the word "permeability" restricted to the material structure.

With regard to question 3, for one-dimensional steady flow it seems desirable to use the HAGEN-POISEUILLE equation as a basis for equations expressing the volume of fluid flow in porous media. The basic equation is:

$$Q = Cd^2 \frac{\rho}{\mu} gAi \quad \text{. . . . .} (1)$$

In equation (1) the symbols, definitions, dimensions, and f.p.s. units are:

Symbol	Definition	Dimension	fps unit
Q	Volume flow in unit time	L^3/T	cubic feet/sec.
d	Diameter of pipe	L	feet
ρ	Fluid density	FT^2/L^4	lb. sec.^{2}/ft.^{4}
μ	Viscosity	FT/L^2	lb. sec./ft.^{2}
g	Gravitational acc. constant	L/T^2	ft./sec.^{2}
A	Area normal to flow	L^2	ft.^{2}
i	Hydraulic slope	(abstract number)	---
C	Coefficient	(abstract number)	---

In the application of equation (1) to fluid flow in a porous media, it is suggested that the Committee consider the advisability of recommending the following usage:

Physical quantity	Parameter symbol	Dimension	fps unit
Permeability	Cd^2	L^2	ft.^{2}
Viscosity	μ	FT/L^2	lb. sec./ft.^{2}
Fluid density	ρ	FT^2/L^4	lb. sec.^{2}/ft.^{4}
Conductivity	$Cd^2\rho/\mu$	T	sec.

The suggested usage presented above would make the "conductivity" equal to permeability times fluid density divided by viscosity. Representing this quantity by k, equation (1) becomes;

$$Q = kgAi \quad \text{. . . . .} (2)$$

Some of the advantages and disadvantages of using a conductivity factor having the dimensions of time were outlined by ISRAELSEN and MORGAN under the heading "Specific water-conductivity (k) of an artesian aquifer" in the Transactions of the American Geophysical Union, Eighteenth Annual Meeting, pp. 573-574. The k there used equals the product $Cd^2\rho/\mu$ of equation (1). The needs and advantages of the usage were summarized as follows:

(1) The cubic foot per second (second-foot) is almost universally used as the unit of flow in hydraulics dealing with surface flow and needs to be used for subsurface flow.

(2) If the "second" is adopted as the time unit in water flow, then it is desirable to select a conductivity factor having the physical dimensions of time. The specific water conductivity, k, has the physical dimensions of time only. It has also the same numerical magnitude when measured in cubic centimeters per square centimeter per second as in cubic feet per square foot per second--thus making it readily adaptable to laboratory and field use.

(3) From an educational standpoint there is advantage in explicit use of the acceleration constant, g, in the flow equation.

(4) The use of a new conductivity factor seems to be needed for and wholly consistent with the application of the potential, and the potential gradient--physical concepts of real value in the basic studies of soil-water movement.

The only evident disadvantage in the use of the term proposed--specific water conductivity--is the fact that its numerical magnitude for nearly all soils is small. However, this may be largely overcome by the use of a term 10^{-x} as a factor in the number.

Replacing the product ρg of equation (1) by the specific weight of the fluid, γ, there results:

$$Q = \frac{Cd^2\gamma}{\mu} Ai \quad \ldots\ldots (3)$$

Expressed in words, the conductivity factor of equation (3) is permeability times the fluid specific weight divided by viscosity. It has the dimension of velocity.

Let $k_s = \frac{Cd^2\gamma}{\mu}$ and equation (3) becomes:

$$Q = k_s Ai \quad \ldots\ldots (4)$$

in which k_s represents basically the much-used "transmission constant" and "coefficient of permeability."

If it should be decided advisable to restrict the meaning of the term "permeability" to represent the structure of the porous media, Cd^2, as herein suggested; and if the word "conductivity" is used to designate the k of equation (2), in which the gravitational acceleration constant, g, is explicit; then a new term may be needed for the conductivity factor, k_s, of equation (4) in which g is implicit. Perhaps the word "conductivity" might be used without confusion to mean either k or k_s by adding the physical dimension to indicate which quantity it represents. Thus, "conductivity (T)" would represent the quantity k of equation (2), and "conductivity (L/T)" would represent the quantity k_s of equation (4).

For the measurement of water conductivity of coarse-textured soils under field conditions, variations in viscosity, due to temperature changes, are very small compared to variations in the "permeability," Cd^2, of equation (1). The "structure of the material" is the dominant parameter. Changes in the fluid properties usually may be neglected. On the other hand, for very fine-textured clay soils, in which the "permeability," Cd^2, is very low--possibly only one-millionth that of its magnitude for gravelly soils--it may be essential to consider changes in the viscosity and in the specific weight in order to obtain desired accuracy.

W. C. KRUMBEIN (Gulf Research and Development Company, Pittsburgh, Pennsylvania)--It is my belief that the coefficient of permeability should depend only on the properties or structure of the material, and should be entirely independent of the fluid. Permeability is important to a wide range of problems in many fields, including fluids of all sorts in media of many kinds, and exactly the same basic physical laws apply. Each field will do well, therefore. to relate its own problems to these basic principles, so that advances in any other field become directly applicable to its own problems. We need only consider the many relations between ground-water problems and oil-field problems (both drainage and flooding) to see how a common or at least convertible set of definitions will help both fields.

Although I am strongly in favor of a permeability.unit independent of the fluid, I can see a number of advantages to a field unit which includes the fluid. As far as possible, however, such field units should be convertible to units expressed in terms of the material only, with due regard for the dimensions of each kind of unit. For these practical units, some other name should be chosen. THEIS'S "coefficient of transmissibility" is the kind of term I have in mind.

As to the parameters that should be included in the equation of flow as they relate to the structure of the material, I am inclined to follow M. KING HUBBERT'S analysis, which provides a sound physical basis for setting up units. The darcy has come into wide use as a unit in some fields, but it is perhaps too early to recommend it as a standard unit for all fields interested in the problems of fluid flow through permeable media. My own interest lies mainly in the relation between the fundamental properties of the medium (such as the size and shape distributions, the particle orientation, and the general packing effect) and its permeability.

W. B. LANGBEIN (Geological Survey, U. S. Department of the Interior, Washington, D. C.)--With reference to question 1, WEBSTER defines "permeable" as capable of being penetrated and gives as an example "wood is permeable to oil" suggesting that material and fluid must both be expressed. One might safely generalize that wood is permeable to any fluid having the properties of oil and indeed we know that if wood is permeable to oil it is permeable to any fluid, if appropriate allowance is made for different rates of flow and loss of pressure, etc. Since those properties of fluids that govern fluidity (that is, allow a fluid to permeate) are measured by viscosity, it appears convenient to treat permeability separately as a property of the material and the coefficient of permeability as a measure of that property, assuming that there is no physical or chemical reaction between fluid and medium.

With reference to questions 2 and 3, if as in ground-water work the fluid is always understood to be water, then a unit that expresses the combined property may be desirable. In this case (as in MEINZER'S working formula) in effect the fluid used as basis for comparison (that is, water at 60°F.) is defined as having a viscosity of unity. If this is kept in mind the coefficient may be still properly called "coefficient of permeability." The unit called the "darcy" may have some merit in hydrologic work because water has a viscosity of one centipoise (dynamic), or one centistoke (kinematic) at a temperature of about 68°F.

In this connection the question may be raised as to whether "DARCY'S law" ever contained any factor for viscosity or other fluid properties. It seems that DARCY'S contribution was rather the application of the prior HAGEN-POISEUILLE discoveries to flow of water through sands.

Users of DARCY'S law I believe will continue to find it practical to use measures common to their particular business. Moreover, hydrologists and construction engineers continue to function on the basis that the fluid is water and will therefore use a formula in which viscosity is implied if not expressed. Petroleum geologists may be concerned with air, gas, oil, or water and accordingly must use an equation in which viscosity and density are expressed. Nevertheless, some common denominator would be a desirable convenience to which all can refer as a standard for intercomparisons of permeable materials. To this end the writer suggests that the HAGEN-POISEUILLE equation for laminar flow be employed rather than the DARCY simplification. The units of permeability now used are commonly hydrometric, that is, involving rates, gradients, and other factors. The unit suggested herein is physical, being definitive of the material. I think this approach may have some merit on that account. The HAGEN-POISEUILLE equation

$$V = i(D^2 \rho g/32\mu)$$

is exact and dimensionally correct. Let Q/A equal apparent velocity. Then

$$Q = Ai(D^2 \rho g/32\mu)$$

where

i = total energy gradient

ρ = density

g = gravity

μ = dynamic viscosity

The viscosity and density are properties of the fluid; diameter of the conduit is the only measure of the conduit involved. So long as the flow is laminar it does not matter what the character of the conduit is; the important thing is the fluid properties. There are no coefficients. Here we have an equation for flow that contains no empirical coefficients of proportionality, a unique condition in hydraulics.

The only unknown is D, the diameter of a tube that under the given conditions conveys laminar flow with velocity equal to Q/A. It is a measure of the properties of the aquifer only.

All literature uniformly reports textural sizes in millimeters, and capillary tubes are also generally so reported. Here then is a unit on which possibly many can agree.

The use of D or an "equivalent capillary" diameter is a measure of the aquifer that has direct physical significance that may appeal to many. For MEINZER'S unit of 1, the value of D is 0.00132 mm, suggesting a clay or a consolidated sand. For MEINZER'S unit of 1,000,000 the value of D is 1.32 mm, suggestive of an open gravel of fissured or channeled rock. For a darcy the value of D is 0.00565 mm, and for a millidarcy it is 0.000179 mm. A disadvantage of the "equivalent capillary" diameter as a permeability unit is that its computation requires the extraction of square root.

O. E. MEINZER (Geological Survey, U. S. Department of the Interior, Washington, D. C.)--In response to the memorandum of December 2, 1943, I offer the following comment:

1. The coefficient of permeability depends only on the nature of the material (not on the fluid). However, it can be expressed in terms of a fluid having specified viscosity and density, such as pure water at a specified temperature.

2. The term coefficient of transmissibility has been used for some time by the Geological Survey to express this concept. It appears to me to be a good term regardless of the units used. This coefficient is based on the flow of the existing fluid at the existing temperature, in a permeable formation, per unit gradient and unit of width of the conduit formed by the formation (measured at right angles to the direction of flow).

MORRIS MUSKAT (Gulf Research and Development Company, Pittsburgh, Pennsylvania)--The first question pertains to the definition of the coefficient of permeability, and its relationship to the structure of the porous material and the characteristics of the fluid passing through it. In this connection WENZEL may possibly have anticipated my reaction which is based on our experience and established practice in the oil industry, namely, that the viscosity coefficient should be segregated from the structural effects and the permeability should refer only to the latter. I feel that this point of view is founded on sound physical considerations. Moreover, it is virtually a practical necessity, since in the oil industry we have to deal in general with three different fluids, namely water, gas, and oil, the last of which may vary widely in viscosity from field to field. It is, therefore, impossible to standardize on the permeability with a particular fluid, as that would be nothing more than a fiction and of no significance. On the other hand, I fully appreciate that the situation is different in the field of ground-water hydrology where, except for the limited temperature variations, the fluid of interest can be accepted as universally fixed. In this case, I believe that there are sound practical reasons for absorbing the viscosity of the fluid into the factor of the permeability representing the structure of the material, and combining the two into a single unit. Although we in the oil industry frequently claim that our unit of permeability is based only upon physical considerations, it is, of course, founded equally on the practical necessities of the problems that we encounter in practice. I can, therefore, see no reason to insist that in the field of hydrology practical questions should be given less weight or perhaps even entirely ignored. The important thing, it seems to me, is that there be established agreed definitions to be applied in the different fields and that the appropriate conversion factors be made available to permit a ready interchange of the material developed in the several types of activity.

Along the same line it may be noted that the textile industry or the ceramic industry may also well claim the right to define the permeability in terms of a single fluid, such as air, which may be a practically universal medium for these types of activity. I feel that they, too, should have equal privileges for combining into the coefficient of permeability the properties of the fluid of exclusive interest to them, provided only that such usage is explicitly indicated in their symbolism and terminology so that conversion factors may be derived in terms of other units.

The second question is related to the first, at least from the point of view I have discussed above. You probably know that in the oil industry, the unit "darcy" has been established. I see no reason for a change in this name. If, however, units and coefficients were to be adopted where air or water were to be incorporated in the flow system then individual names may be appropriate, such as the name "dar" which I understand has been accepted in the hydrologic field.

Assuming that there is a basic agreement regarding the definition of permeability, and that except for the viscosity the permeability is independent of the fluid, then of course, it does not matter what permeameter is used for determining the coefficient. Suitable experimental precautions and careful handling of the units used should insure that equivalent results may be obtained with any permeameter constructed on the basis of sound physical principles. I refer, of course, only to laboratory measurements. With respect to field experiments for permeability determination, such as mentioned in your letter, I must confess that I am somewhat dubious about the value of bringing in such determinations into any generalized basic treatment of the permeability problem. Otherwise one immediately encounters questions regarding the appropriate formulas to be used, and perhaps the approximations in these formulas, and finally uncertainties pertaining to the influence of entirely extraneous factors. For example, in the petroleum industry it has been found that in some districts the field determinations of permeability differed largely from tests on small rock samples from the same wells. I don't know if similar difficulties have arisen in the investigation of ground-water systems or in other fields, but I do feel that the uncertainty regarding so many of the basic data which arises in almost all field experiments is of such a different order from that encountered in laboratory experimentation that the two types of measurements should be definitely separated, and that, moreover, only the latter should be relied on for the basic establishment of permeability values. Of course, I do not mean to imply any doubt as to the value of field measurements from a practical point of view. We have found them to be absolutely necessary, in spite of their radical differences from laboratory experiments. However, I do believe that they should not be included in the scope of so-called fundamental definitions and procedures for permeability determination.

L. A. RICHARDS (U. S. Regional Salinity Laboratory, Riverside, California)--I spent considerable time and thought on this subject a few years ago and concluded there is not much hope of choosing or defining a permeability unit that would be suitable for general use in all or most of the fields of work in which permeability is measured.

My paper "Concerning permeability units for soils," in the Proceedings of the Soil Science Society of America, 1940, summarized some of my thinking on the subject, and at that time, I felt that equation 9 on page 52 might be a suitable basis for a definition of a fundamental permeability unit, although I did not state this as my opinion in that paper. The final paragraph of the paper, however, may be worth some consideration by the Subcommittee.

To make clear my position, I would like to propose that among other things related to permeability, the Subcommittee on Permeability endeavor to promote:

(1) The selection and naming of a general, fundamental permeability unit for the flow of fluids through porous media.

(2) The practice of publishing permeability data in terms of the above unit, in addition to any particular preferred unit that might be used in a particular field.

I have the following comments to make on the points which WENZEL invited discussion in his letter of December 2, 1943:

(1) Permeability should be defined so as to depend only on the structure of the medium. It may be desirable not to use the word permeability in connection with the new unit. Fluid conductivity or some other term could be used.

(2) I feel that a name for the new unit should very definitely be chosen and clearly designated.

(3) The parameters to appear in the flow equation will depend, of course, on the selected definition for the permeability unit. If an equation such as (9) referred to above is used, then viscosity and density of the fluid and the acceleration of gravity appear in the equation.

U. S. Geological Survey
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APPENDIX B--NOTES ON THE PERMEABILITY COEFFICIENT AND ITS UNITS

V. C. Fishel

In the development of terms and units for a new science such as ground-water hydrology, which is based on physics, it would seem fitting to adopt the terminology that has become standard in other branches of physics such as heat and electricity. DARCY'S law has its counterpart in similar laws in the other branches of physics.

Possibly much of the confusion regarding the use of the permeability unit in ground-water hydrology could be eliminated by following established terminology in physics and eliminating the term "coefficient." This might eliminate the necessity of having such terms as "field coefficient of permeability," "laboratory coefficient of permeability," "transmission constant," and others as will be explained later. The word "coefficient" is defined in WEBSTER'S Dictionary as follows:

(1) (Mathematics) Any numeral or literal symbol placed before another symbol or combination of symbols as a multiplier.

(2) (Physics) A number expressing the amount of some change or effect under certain conditions as to temperature, length, volume, etc.

(3) A number indicating the degree of a quality possessed by a substance, either permanently or under fixed conditions; as, the coefficient of expansion of iron.

The last definition seems to fit the present use of the expression--"coefficient of permeability." The example given for the last definition fits the second definition as the coefficient of expansion of iron is the amount of change per degree of temperature.

Coefficient of viscosity. The use of the word "coefficient" in connection with viscosity is almost identical with our use of the word in connection with permeability. The coefficient in both cases has dimensions. Most text books use the expression "coefficient of viscosity" but many of these same books use "coefficient of viscosity" and "viscosity" interchangeably.

The restricted use of the word "coefficient" will be illustrated by a number of definitions taken from the 21st edition of the Handbook of Chemistry and Physics:

"Temperature resistance coefficient--The ratio of the change of resistance in a wire due to a change of temperature of 1°C to its resistance at 0°C.

"Coefficient of linear expansion--The fractional part of its length that a rod elongates when raised one degree in temperature. (A dimensionless quantity.)

"Coefficient of volume expansion--The increase in volume of a unit cube for one degree rise in temperature. The coefficient of cubical expansion is three times the coefficient of linear expansion in an isotropic body. (A dimensionless quantity.)"

The "coefficient of expansion" as applied to liquids is a term that is comparable to what the term "coefficient of permeability" could suggest; in other words, the term "coefficient of permeability" could mean the change in permeability per degree change in temperature. The expansion of liquids per degree varies with the temperature. Thus water will have a different coefficient of expansion at 20°F than it will at 80°F. Likewise, the change in permeability per degree of temperature of porous media is different. Thus if we used "coefficient of permeability" in the same sense as it is used in heat and electricity, the coefficient of permeability would vary as the coefficient of viscosity.

The term "permeability" in hydrology could be used in the same sense as resistance in electricity. We speak of a given electrical circuit as having a given resistance, which is a correct and satisfactory statement for practical purposes. The resistance, however, is a function of the temperature. In all metallic conductors the resistance increases as the temperature increases. The specific resistance is the resistance of unit cross-section and of unit length at 0°C. When the resistance of an electrical conductor is measured the actual resistance is given in ohms and not the specific resistance. We could follow the same procedure in ground-water hydrology. When we make a pumping test there seems to be no reason why we could not say that the aquifer has a permeability of so many meinzers, darcys, dars, or other term at the existing temperature. Following the same line of reasoning the standard coefficient or laboratory coefficient of permeability could be called the "specific permeability."

It seems to me that terms such as "field coefficient of permeability" and "laboratory coefficient of permeability" are misleading. One would assume that the term "laboratory coefficient" implies that it was determined in the laboratory, whereas it was meant by WENZEL to mean the standard coefficient (specific permeability), and may have been determined by a pumping test in the field. It seems to me that the same terminology should apply whether the permeability was determined in the laboratory or in the field. If a pumping test were made at a temperature of 62°F. we could correctly say that the material has a permeability of so many (name of unit) at a temperature of 62°F. It is doubtful if anyone would ever be interested in the permeability at 60°F (or at the temperature of the standard unit), but it could easily be computed by anyone if the data were given.

The terms "field coefficient of permeability" and "transmission constant" might imply that an aquifer has a constant permeability. In an area of salt-water encroachment, the permeability may change as the density of the water changes. Also the temperature of the water in alluvium may change considerably, resulting in a change in the permeability, if increased pumpage results in a large increase in the recharge from the river. If we omit the use of the word "coefficient," the term "permeability" like the term "resistance" is not rigid and it can be adjusted for changes in the field conditions.

Definitions will now be given of some electrical terms that are comparable to the term "permeability" or to the reciprocal of permeability to illustrate the use of the word "specific" in the definition of terms in physics. The usage is identical with MEINZER'S usage in connection with specific yield or specific retention. Thus an aquifer will have a given yield under given conditions, but the specific yield is the ultimate yield under standard conditions:

"Resistivity or specific resistance--The resistance of a body of the substance of unit cross-section and of unit length at 0°C.

"Conductance--The reciprocal of resistance, as measured by the practical unit, the Mho, is the conductance of a body through which one ampere of current flows when the potential difference is one volt.

"Conductivity or specific conductance--is measured by the quantity of electricity transferred across unit area, per unit potential gradient per unit time."

The adoption of a standard permeability unit will be difficult if not impossible. Each organization has its own pet unit which it has adopted because of its convenience for its own particular use, and there would be reluctance to change to another unit. If a standard unit were adopted each organization would want to continue the use of a practical unit. Thus ground-water hydrologists who have become accustomed to using gallons per day would be reluctant to abandon this unit in favor of a unit based on the cgs system. In a personal communication L. A. RICHARDS made the following excellent suggestion regarding the selection of a standard permeability unit:

"At present I am inclined to hope that through cooperative effort we shall be able to select and name a standard permeability unit that will be acceptable, at least as second best, by the majority of workers in different fields. By this I mean, taking your own laboratory, for example, you may deem it wise to continue using MEINZER'S coefficient but if you were to publish your data in more than one permeability unit you would use the standard unit."

I personally favor the retention of MEINZER'S unit for our practical use in the Geological Survey but would have no objection to the adoption of a standard unit and the publication of our results, either in both units or in MEINZER'S unit and include a conversion factor for changing MEINZER'S unit into the standard unit.

Presumably a standard unit would be based on the cgs system of units. Several excellent cgs units are already being used and consideration should be given to the adoption of one of them. It is often convenient to use metric units in the laboratory and English units in field work. Thus a unit having the dimension of time has considerable merit as it would have the same numerical value in metric units (measured in cubic centimeters per square centimeter) as in English units (cubic feet per square foot) if the same unit were used. A unit that would be applicable for all fields of permeability should have the acceleration due to gravity explicit to cover vertical as well as horizontal flow.

A name for the unit of permeability would be convenient. The practical unit of quantity in electricity is the "coulomb." It is represented by the flow of one ampere of current for one second. It is much more convenient to use coulombs than to use ampere-seconds or volt-seconds per ohm. It would likewise be much more convenient to say that an aquifer has a permeability of 100 (name of unit) than to say it has a permeability of 100 gallons per day per square foot, or similar expression.

Summary--Examples have been given of some terms in heat and electricity to illustrate the use of the word "coefficient" and it is suggested that the word "coefficient" should be dropped from the expression "coefficient of permeability." Objections are given to the terms "field coefficient of permeability," "laboratory coefficient of permeability," "transmission constant," and other similar forms. It is then suggested that the quality of a material that is now known as the coefficient of permeability or laboratory coefficient of permeability be called "specific permeability" in comparison with the use of the term "specific resistance." It is then suggested that if the permeability is determined for other than standard conditions (field conditions) that we omit the word "specific."

I have recommended that the Geological Survey retain MEINZER'S unit as a practical unit but that we adopt a standard unit in cooperation with others interested in permeability studies, and that our results be published for both units or in terms of MEINZER'S unit and a conversion factor. I would recommend that the standard unit be based on the cgs system, have the dimension of time, and have the acceleration due to gravity explicit in the equation.

I have recommended that the units be named. I think the practical unit in the Ground-Water Division of the Geological Survey should be called the "meinzer." The name for the standard unit will depend on the unit chosen and on the organizations cooperating in the establishment of the unit.

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APPENDIX C--PERMEABILITY: ITS DIMENSIONS AND MEASUREMENT

M. King Hubbert

Introduction

Although a great deal of progress has been made during the past few decades toward a complete understanding of the various factors governing the flow of fluids through sands and other permeable solids, there still exists among the various individuals and groups concerned with such problems an unnecessary diversity of usage as regards the form of the flow equations employed, and the units of measurement used. A uniformity of usage among the various students of this subject has obvious advantages, but before that can be achieved, agreement is required as to the optimum form of the equations of flow, and the definitions to be given the related parameters.

It is here suggested that the simplest and most direct approach to the solution of this problem is to be found by returning to first principles and setting up the equations in accordance with the established conventions of analytical mechanics. In this manner the derived equations of flow assume their simplest form and are valid independently of the units of measurement ultimately to be used. An outline of such a treatment, emphasizing dimensional relationships to be observed, follows.

The Conventions of Mechanics

Dimensions of mechanical quantities--In mechanics, although more than a dozen quantities of different kinds have been defined and are in common use, only three of these are mutually independent. If A, B, and C be any three such quantities which may be chosen as the fundamental ones of a system of measurement, then it will be found that in the definition of any of the remaining quantities each fundamental quantity will occur as a multiple or a root an integral number of times. Hence any derived quantity may be defined in terms of the quantities chosen as fundamental by a formula of the type

$$(Q) = (A^{\alpha}B^{\beta}C^{\gamma}) \quad \ldots\ldots\ldots\ldots \quad (1)$$

The exponents α, β, and γ, which will be integers or rational fractions, are said to be the dimensions of the quantity Q in terms of A, B, and C taken as fundamental.

It is to be noted particularly that the characteristics that distinguish mechanical quantities of one kind from those of another are their dimensions and not the units by which they are measured. Thus the class of quantities having the dimensions ML^{-3} and that having the dimensions MLT^{-2} in terms of mass, length and time taken as fundamental, are called density and force, respectively, regardless of the units in which they may be measured. The same should apply to any new kind of mechanical quantity which may be defined for any particular purpose. It should be defined in terms of dimensions and its name based solely upon that definition.

Units of measurement--Having selected three mutually independent mechanical quantities as the ones to be regarded as fundamental, units of measurement of constant magnitude may be chosen for each. Let these be a, b, and c, respectively, for the three quantities A, B, and C. We may then define the unit of any derived quantity Q in terms of the units of the fundamental quantities by an equation of the form:

$$(q) = (a^{\alpha} b^{\beta} c^{\gamma}) \qquad (2)$$

In this manner, again taking mass, length, and time as fundamental, the unit of area becomes an area equal to that of a square whose side is a unit of length; the unit of volume is the volume of a cube whose side is a unit of length; the unit of density is the density of a unit of volume containing a unit of mass uniformly distributed; the unit of velocity is a displacement of unit distance in unit time; etc.

Mechanical equations--When the foregoing conditions are observed the equations of mechanics assume their simplest form and are capable of algebraic representation which is valid independently of what quantities may be taken as fundamental and of what the units of measurements of these quantities may be. Every enumeration of a mechanical quantity consists essentially of two parts, the first a pure number, and the second a statement of the unit of the thing enumerated. Since the laws of addition are valid only when each term is an enumeration of units of the same kind, it follows that valid equations in mechanics can likewise consist only of terms enumerating units of the same kind, which is equivalent to stating that every term must represent a quantity having the same dimensions, or that mechanical equations must be dimensionally homogeneous.

The equation for the distance traveled in uniformly accelerated motion affords a simple illustration:

$$s = s_o + v_o t + at^2/2 \qquad (3)$$

where s is the distance at time t, s_o the initial distance, v_o the initial velocity, and a the acceleration. Supplying the units of measurement this is equivalent to

$$s\ (\ell) = s_o\ (\ell) + v_o t\ (\ell t/t) + (at^2/2)(\ell t^2/t^2) \qquad (4)$$

Since in the last two terms the units of time cancel out, it will be seen that the algebraic symbols in every term are an enumeration of the unit of length ℓ.

The equation for the flow of fluids through sands

With due regard to the principles set forth above, let us consider now the problem of the general formulation of the equation of flow of fluids through sands. Essentially what we wish is to express the rate of flow, as the dependent variable, as a function of all the other factors, regarded as independent variables, which determine the rate of flow. Although the relations involved are capable of being derived directly from first principles, we shall here be content with a statement of what they are, and only an outline of their derivation. For the quantity that characterizes the rate of flow we may choose either the volume rate or the mass rate. In an arbitrary direction s we may let q_s be the average volume of the fluid crossing unit area normal to s in unit time, or we may let j_s be the average mass of the fluid crossing unit of area normal to s in unit time. Since mass is the product of the density and the volume it follows that

$$j_s = \rho q_s \qquad (5)$$

For liquids, which are ordinarily measured by volume, q_s is perhaps preferable; for gases, j_s is to be preferred in view of the constancy of the fluid mass.

The factors which determine the rate of flow are ultimately the forces which act upon the fluid. These may be distinguished as the forces whose combined effect is to drive or impel the fluid, and those which are brought into action by the motion of the fluid, whose net effect is to resist the motion. The former we may refer to as the driving forces, and the latter as the reactive forces.

The driving forces are of the nature of imposed forces and are two in number. One arises from the pressure gradient existing within the fluid, and the other is the force exerted upon the mass of the fluid by the gravity field of the Earth. Referring these forces to unit mass of the fluid, the intensity of the driving force in the direction s will be

$$E_{ds} = E_{gs} + E_{ps} = g_s - 1/\rho(\partial p/\partial s) \qquad (6)$$

where ρ is the density of the fluid, g_s the component of gravity in the s-direction, and $\partial p/\partial s$ the rate of increase of pressure in the s-direction.

The reactive forces are also two in number, that due to the viscous resistance of the fluid and that due to the inertial reaction of the fluid to accelerated motion. For a single small volume element of the fluid in similar states of flow, the component of the force per unit of mass due to acceleration in the direction s will be

$$E_{is} = a_s \sim q_s^2/d \quad \text{. . . . .} (7)$$

and that due to viscous resistance will be

$$E_{rs} \sim -q_s\mu/\rho d^2 \quad \text{. . . . .} (8)$$

where a_s is the component of the acceleration and q_s the volume rate of flow, or specific volume discharge, in the direction s, μ the dynamic viscosity of the fluid, ρ the fluid density, and d a statistical length parameter, such as the average grain diameter, characterizing the coarseness of the sand.

In statistically parallel rectilinear flow through a uniform sand, the acceleration a_s will be as often negative as positive so that the average value of inertial reaction over a finite volume will be zero. Its real effect, however, is to produce distortion in the form of the lines of flow as the velocity is increased so that for the same fluid and sand similarity cannot be retained at different velocities and the viscous resistance will increase with increase of q_s faster than indicated by equation (8). If we form the ratio of the inertial force per unit of mass to that of resistance we obtain

$$E_{is}/E_{rs} = (q_s^2/d)/(q_s\mu/\rho d^2) = q_s d/(\mu/\rho) \quad \text{. . . . .} (9)$$

which for any given sand and fluid can be made to approach zero by sufficiently reducing q_s. Then if we agree to keep q_s small enough that

$$E_{is} \ll E_{rs}$$

the inertial term drops out entirely and similarity is maintained for all such velocities, leaving as the equation of equilibrium of the forces-per-unit of mass

$$E_{ds} + E_{rs} = 0 \quad \text{. . . . .} (10)$$

Substituting values for these terms from equations (6) and (8) then gives

$$g_s - 1/\rho(\partial p/\partial s) - q_s\mu/N\rho d^2 = 0$$

where 1/N is a dimensionless factor of proportionality for equation (8). Solving this for q_s, we obtain

$$q_s = (Nd^2\rho/\mu)[g_s - 1/\rho(\partial p/\partial s)] \quad \text{. . . . .} (11)$$

which is the general equation of motion of a fluid flowing through a sand or any comparable solid skeleton network, subject only to the condition that inertial forces are negligible. This contains all that is essential in what has come to be known as "DARCY'S law." The only undefined quantity is the factor N, which depends simply upon the shape of the internal structure of the flow system. For two flow systems all of whose parameters except that of shape are the same, it is to be expected that the rates of flow will differ. This difference is reflected by the factor N.

Equation (11) can be expressed in a variety of equivalent ways. Defining the potential Φ of the system as the mechanical energy per unit of mass at any given point, then

$$\begin{aligned} \Phi &= \Phi_o - \int_{p_o}^{p} [g_s - 1/\rho(\partial p/\partial s)]ds \\ &= \Phi_o + g_s(z - z_o) + \int_{p_o}^{p} dp/\rho \quad \text{. . . . .} (12) \end{aligned}$$

where z is positive in the upward direction. Then

$$-\partial\Phi/\partial s = [g_s - 1/\rho(\partial p/\partial s)]$$

and equation (11) becomes

$$q_s = -(Nd^2\rho/\mu)\partial\Phi/\partial s \quad \text{. . . . .} (13)$$

When dealing with the flow of a liquid, especially in ground-water flow, it is often convenient to employ a manometer terminated at a given point as a measuring device. If z is the elevation of

the point of reference above a standard datum, and h the height to which the liquid rises in an open-topped manometer above the same datum, then the potential at the point of reference will be

$$\Phi = \Phi_0 + g(z - z_0) + (p - p_0)/\rho = gh \quad \text{. . . . . (14)}$$

Consequently,

$$\partial\Phi/\partial s = g(\partial h/\partial s) \quad \text{. . . . . (15)}$$

Making this substitution in equation (13) gives as an equivalent form

$$q_s = (-Nd^2\rho g/\mu)\partial h/\partial s \quad \text{. (16)}$$

The problem of permeability

The equivalent equations (11), (13), and (16) express all that is essential regarding the motion of fluids through sands within the domain embraced by DARCY'S law. Since the principal interest of this Subcommittee centers upon the disentanglement of the concept of permeability, and its measurement, that problem needs still to be considered.

The concensus of opinion among the various students of this problem appears to be definitely that the term "permeability" should express a property of the medium only and should be independent of the properties of the fluid. Furthermore, from the general meaning of the term, of two sands through which the same fluid is made to flow under identical conditions, that one for which the rate of flow is the greater has the greater permeability.

Examination of the flow equations shows that of the several independent variables, ρ and μ are properties solely of the fluid, $g\partial h/\partial s$ or $\partial\Phi/\partial s$ represents the impressed force per unit of mass, and only the geometrical product (Nd^2) characterizes or depends upon the solid medium through which the flow occurs. Therefore, if permeability is to be a property of the medium only it must necessarily be a function of the factor (Nd^2). The simplest possible definition then becomes

$$(\text{permeability}) = (k) = (Nd^2) \quad \text{. . . . .(17)}$$

which is a dimensional definition and is independent of what mechanical quantities may be taken as fundamental, or of what units of measurement may be employed.

The measurement of k is accomplished hydrodynamically. Solving equation (16) for k gives

$$k = -\mu q_s(\rho g\partial h/\partial s) \quad \text{. . . . .(18)}$$

for which all of the factors in the right-hand term are capable of direct measurement.

Systems and units of measurement--The dimensions of k are the same as those of the combined term to the right but these cannot be specified until the quantities to be regarded as fundamental are chosen. Obviously k will have unit value when a fluid of unit viscosity and density flows with unit specific volume discharge under unit impelling force per unit of mass, or due to unit value of gravity and unit hydraulic gradient. In view of this fact the temptation exists to assign units of measurement to q_s, μ, and ρ, or to some other combination of the quantities in the right-hand term of equation (18) in such a manner that the unit of k will be psychologically easy of comprehension, and at the same time will be of a magnitude within or near the range of values of the permeability commonly encountered in sediments.

Although this is the procedure that has most often been followed in practice, it is illusory and can only lead to trouble as can easily be shown. All possible combinations of fundamental quantities can be divided between those which do and those which do not contain length. For all systems which do contain length as one of the fundamental quantities the dimensions of k are simply length squared. For all systems which do not contain length we are confronted with the necessity of defining primary units of measurement for such quantities as density, viscosity, velocity, acceleration, and force and then measuring and expressing all lengths in terms of combinations of these units. Since length is the most familiar and the most often measured of all physical quantities it is quite impracticable to employ any system of measurement which does not contain length as one of its fundamental quantities. We are left, therefore, with no choice whatever for the unit of permeability, if consistent units of measurement are to be employed, other than

$$(\text{unit of permeability}) = (\text{unit of length})^2 \quad \text{. . . . .(19)}$$

Hence, the only arbitrary choice which we have at our disposal is that of the unit of length. In this choice two conflicting alternatives exist. If we choose a unit of length of the order of magnitude of the length of the human body, which is convenient for the operations of direct measurement, we shall find that the permeabilities of the common sediments will be only a minute fraction of the unit of permeability thus determined; if we define the unit of length in such a manner that the values of the permeability of the most sediments fall within the range of 1 to 10^3, then this unit of length would be but a minute fraction of the length alternatively considered. For example, if we choose the centimeter as the unit of length the unit of permeability becomes the cm^2. In terms of this unit the values of the permeability of the sediments from silty clay to coarse gravel range from about 10^{-14} to 10^{-5} cm^2. Alternatively, if we choose a unit of length such that most of the measured values of permeability fall in the range between 1 and 10^3 (unit of length)^2, the unit would have to be about 10^{-5} or 10^{-6} cm.

Between these conflicting alternatives no compromise is possible. Since, however, permeabilities are not measured directly, but are obtained only indirectly by calculation from the measured quantities of equation (18), the unit of length figures in the expression for the magnitude of the permeability only as a calculational quantity. On the other hand, the unit of length must be employed directly as a unit of measurement in the evaluation of the independent variables of equation (18). In consideration of these facts, there is again no practical alternative but to choose a unit of length which is suitable for direct measurement. The computed permeabilities can then be conveniently and unambiguously written in the form

$$k = n\ 10^{-m}[(\text{unit of length})^2]$$

where n is a small number and m a positive integer.

Since an ample number of standard units of length already exist there is no need to define another. Neither is there need for any official action authorizing or sanctioning any particular unit of length as the proper one in which permeabilities are to be expressed. All that is required is that in every instance the unit, such as the ft^2 or the cm^2, be specified along with the numerical magnitude. This, however, is not a requirement peculiar to the measurement of permeability, but one common to measurements of every kind. It is meaningless, for example, to say that a length is five without also specifying the unit of measurement, whether the foot, the centimeter, or the mile.

Importance with regard to analysis--Although adherence to a system of consistent units in accordance with the established conventions of mechanics is warranted in all cases by the simplicity to which it leads, its greatest usefulness lies in the manner in which it facilitates analysis. Fluid-flow problems are often sufficiently complex that algebraic analysis is necessitated. Provided the conventions regarding the consistency of units is conformed to, the algebraic equations are of general validity independently of what system of units may ultimately be employed. The importance of this fact alone outweighs all other considerations as to the superiority of consistent units over any system of inconsistent or so-called "bastard" units of measurement.

Intercomparison of existing units

In view of the fact that a number of units for the measurement of permeability have previously been defined, and that some of these are in use, it may be worthwhile to make a brief intercomparison of a few of the better known of these. In defining their units the procedure followed in all cases by the original authors has been to express permeability by some equation analogous to (18) and then to prescribe the units of the independent variables for which the permeability is defined to have unit value. So long as the permeability so defined is a property of the medium only, the value of k as herein defined corresponding to any other specified unit can also be obtained from the same data. This may be done by introducing the values of the independent variables prescribed for the given unit, converted to standard units, into equation (18), or its equivalent, and solving for k.

Comparative data treated in this manner for three different units are presented in Table 1. Of these, that of MEINZER and STEARNS [see "References" at end of Appendix, 1928] is extensively employed in ground-water hydrology in the United States, that of WYCKOFF and associates [1934] in petroleum engineering, whereas the unit of NUTTING [1930] has the distinction of being one of the few proposed units which is an exact submultiple of the square of a standard unit of length.

None, however, satisfies the conditions herein outlined as to consistency of prescribed units and is suitable as a rational unit of measurement. For the MEINZER and the WYCKOFF units, this is obvious; for the unit of NUTTING, however, the apparent rationality produced by the exclusive use of multiples and submultiples of rational cgs units is deceptive. This is at once evident when it is noted that in NUTTING'S prescribed system of measurement, units have been assigned to four different mechanical quantities, namely, length, time, viscosity, and pressure, whereas only three of these quantities are mutually independent. Thus if units for length, time, and viscosity are chosen, the unit for pressure is determined; or if units for length, time, and pressure are prescribed, the unit for viscosity is fixed. In either instance the unit of permeability reduces to the unit of length squared, as it should.

Table 1--Comparison of three proposed units of permeability

Unit of independent variables specified by author	Author and date		
	Stearns (Meinzer) 1928	Nutting 1930	Wyckoff, Botset, Reed 1934
Specific volume discharge	$\frac{\text{gal / day}}{\text{ft}^2}$	$\frac{\text{cm}^3/\text{sec}}{\text{cm}^2}$	$\frac{\text{cm}^3/\text{sec}}{\text{cm}^2}$
Viscosity	Water at 60° F	centipoise	centipoise
Density	Water at 60° F		
Pressure gradient		$\frac{10^6 \text{ dynes/cm}^2}{\text{cm}}$	$\frac{\text{atmosphere}}{\text{cm}}$
Hydraulic gradient	1		
Magnitude of unit in			
[cm^2]	5.42×10^{-10}	10^{-8}	0.987×10^{-8}
[ft^2]	5.83×10^{-13}	1.08×10^{-11}	1.06×10^{-11}

Résumé

The concept of permeability is of common interest to all students of the flow of fluids through pervious solids, particularly those whose interests lie in the field of ground-water hydrology, irrigation, and petroleum engineering. The fact that this concept has been given a series of conflicting definitions, and that there have been defined for it a number of incompatible units of measurement, renders it highly important that some thought be given to the means whereby a satisfactory disentanglement may be effected.

It is here suggested that the most direct and, in the long run, probably the only adequate way to solve the problem, is to return to the principles of fundamental mechanics, and to conform to the well-established conventions of that subject.

These conventions are: (1) That definitions of classes of physical quantities shall be based solely upon the dimensions of the various quantities; (2) that arbitrary units of measurement shall be prescribed only for the mutually independent quantities chosen as the fundamental ones of the system; (3) that the units of all derived quantities shall be compounded in accordance with the dimensions of these quantities from the units of the fundamental quantities.

Provided that these conditions are not violated the algebraic analysis of the most diverse of mechanical problems is possible by means of equations whose validity in no manner depends upon the quantities ultimately to be selected as fundamental or of the units of measurement to be chosen for these quantities.

In accordance with these conventions the equation for the flow of a fluid through a permeable solid, subject to the condition that the rate of flow must be small enough that all forces due to inertia are negligible, is

$$q_s = (Nd^2\rho/\mu)E_s$$

where E_s is an impelling force per unit of mass of the fluid. This equation is valid for all fluids, water, oil, or gas.

If the concensus of opinion that permeability should be a property of the medium only is to be followed, the simplest possible definition of permeability is

$$k = Nd^2$$

whose value is measured hydrodynamically by means of the other variables of the equation.

All systems of measurement not involving length as one of the fundamental quantities are impracticable. In all systems for which length is one of the fundamental quantities the dimensions of k are

$$k = L^2$$

so that the unit of k, in accordance with the conventions of mechanics, must be

$$(\text{unit of permeability}) = (\text{unit of length})^2$$

Since ample units of length exist already no new unit need be defined. It is necessary only that the unit in terms of which any given measurement of permeability has been made be specified.

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APPENDIX D--NOTES ON DARCY'S LAW AND PERMEABILITY

C. E. Jacob

In any effort to establish nomenclature relating to the flow of fluids through porous media it would seem well first to consider the history of the development of our concepts and of the terms or expressions involved. Only in this way can precedent rightfully be honored and at the same time duplicating expressions be eliminated and the remaining more useful terms clarified. Then, proceeding with a foresight lined up with recent advances, we may hope to anticipate the needs of the future.

Much of the confusion in our nomenclature has arisen because of failure to recognize precedent for one reason or another. Individual workers have gone ahead often ignoring the contributions of earlier investigators, setting up terms of their own, often duplicating or even contradicting better established usage. This, of course, has been the case in other branches of physical science. Only through the extended efforts of successive international congresses, for example, has the terminology of electricity and magnetism become crystallized.

Action to establish uniform terminology relating to flow through porous media has been sponsored by the Soil Science Society of America. The problems and issues involved in the matter have been very clearly set forth by RICHARDS [see "References" at end of Appendix, 1940A]. Before attempting to decide upon a single universally acceptable permeability unit, wider representation should be sought, both geographically and technically, as suggested by RICHARDS. Workers in other fields such as ceramics, textiles, and soil mechanics should be heard from, formally, through their own technical organizations. In the meantime, however, this Committee might profitably concern itself with naming the different physical magnitudes used in practice to characterize flow systems.

We recognize that while there is strictly speaking only one dimensional combination L^2 that will characterize a given porous medium uniquely, there are three or four useful alternate terms in equivalent equations of flow, each of which differs from the others dimensionally and therefore deserves a distinctive name. If we thus distinguish among them, the matter of selection of units becomes, because of dimensional simplicity, an item of subsidiary concern. Using consistent systems of units that will be widely acceptable the problem resolves itself merely to setting the units within a convenient range of numerical magnitude. If it seems necessary or desirable that may be done as in the metric system by decimal prefixes. Otherwise, positive or negative powers of ten might be used as multipliers [HUBBERT, 1940, p. 923].

The more significant developments bearing on permeability and DARCY'S law are summarized in Table 1. In its preparation the writer has drawn upon original sources as well as upon the excellent summaries by FORCHHEIMER [1914], and by HATSCHEK [1928], and upon the "note on the conditions at the surface of contact of a fluid with a solid body" appearing in the recent Oxford work on fluid dynamics [GOLDSTEIN, 1938]. In addition, the bibliographies given by SLICHTER [1899, p. 381] and by FANCHER, LEWIS, and BARNES [1933] have proved very helpful.

The equations given in Table 1 are reduced to common notation in order to facilitate comparisons. Symbols other than those explained in Table 2, that are not self-explanatory, are as follows: a, b, c, and C′ are (dimensional) constants; C is used as an indiscriminate non-dimensional constant; D is pipe diameter, F_r is resistive force, S hydraulic slope, T temperature, and U "bulk" or average velocity.

Table 1 is offered in the hope that it may supply the necessary background for an appreciation of the work of DARCY, which too often is taken as our starting point. It is interesting to note, and to the writer's knowledge it has not been pointed out before, that DUPUIT [1854] anticipated the results of DARCY'S experiments. He reasoned from the analogy between flow through sand and flow through small tubes. To translate his own words of 1854: "The influence of the head on the discharge of filters has not yet been studied that we know of. If, in awaiting positive experiments it is necessary to rely upon theoretical notions, we would say that the discharge of a filter should be proportional to the head, for each small conduit of the filter may be compared to a tube through which the water moves with a very small velocity. Now, as we shall see later, the resistance of the wall is in this case proportional to the first power of the velocity."

The equation of DARCY is purposely given in Table 1 also in his own notation. It will be noted that his coefficient k has the dimension of velocity. In the work cited he refers to k as "a coefficient depending upon the nature of the sand," "a coefficient depending upon the degree of permeability," and "a coefficient depending upon the permeability of the bed." It would appear that DARCY himself did not use the term "coefficient of permeability." Indeed, in view of the earlier work of GIRARD, who measured specific viscosities before 1816, and of POISEUILLE, who obtained an expression for the relative variation of viscosity with temperature that is acceptable even today, it must be clear that DARCY understood that factors other than the characteristic property (permeability) of his sand bed entered into his k. From either of the three expressions quoted above it may logically be inferred that k is a coefficient depending not solely upon the permeability but also upon the properties of the fluid.

The next step forward was taken by SEELHEIM in 1880 and by HAZEN in 1892, working independently. They introduced the length parameter to the second power characterizing the size of the pores. For the filter sands with which HAZEN dealt, he adopted as a useful "effective size" that diameter of sieve opening through which ten per cent of the grains pass. And to allow for non-uniformity of grain size he introduced an empirical coefficient, the "uniformity coefficient." Both these terms were seized upon and were applied much more widely than HAZEN had ever intended. HAZEN had no specific term to correspond with DARCY'S coefficient.

SLICHTER attempted to integrate by approximation the viscous resistance along an equivalent tortuous capillary of triangular cross section. Though one may question the success of his analytic endeavor, he was the first even to attempt a rational evaluation of the effect of porosity upon permeability. In addition to the factors that had previously been considered, SLICHTER introduced viscosity, density, and acceleration of gravity explicitly into his flow equation. (The corresponding expression, with these same factors, for pipe flow at low velocities had been obtained first in 1845 by STOKES, though the name viscosity was not attached to that coefficient until somewhat later.) However, as a practical matter of ground-water hydraulics, SLICHTER followed the usage of DARCY, DUPUIT, and the others and reverted to the simple expression $Q = kA\Delta h/L$. This k, DARCY'S coefficient, SLICHTER [1899, p. 323] termed "transmission constant," and he defined it as "the quantity (volume) of water that would be transmitted in unit time

Table 1--Résumé of significant developments in connection with Darcy's law and the concept of permeability

Date and source	Contribution	Remarks
1687, NEWTON Principia (English translation by ANDREW MOTTE, 1848)	Hypothesis: That the resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which the parts of the liquid are separated from one another. Experimented with pendulums: $F_r = aU + bU^2 + cU^3/2$ Experimented with falling spheres: $F_r = bU^2 + c$	Erred in application to rotating cylinder; assumed forces on any cylindrical shell must balance. STOKES later showed rather that moments of forces balance; got correct velocity distribution. BERNOULLI, from same data: $F_r = bU^2 + c$
1800, COULOMB, Mém. Acad. sci., v. 3, pp. 246ff	Experimented with torsional oscillation of various discs and cylinders: $F_r = aU + bU^2$ Found resistance independent of material or coating.	Results lead to idea of zero slip at solid boundary.
1804, DE PRONY, Récherchés physico-mathématiques	Analyzed data of COUPLET, BOSSUT, and DUBUAT on resistance in pipe flow: $DS = aU + bU^2$	Formula adopted by EYTELWEIN and by D'AUBUISSON; became standard.
1816, GIRARD, Mém. Acad. sci., v. 1, pp. 187ff	Tested flow through small-diameter copper tubes: $Q = C'D^3\Delta h/L$ Found that resistance decreases with increasing temperature. Tabulated specific viscosities (viscosités spécifiques) for different liquids.	His postulate was: fluid slips over thin stagnant layer, existence dependent upon wetting, thickness dependent upon curvature and temperature. (Eq. given applies to limiting case, stagnant layer of zero thickness.)
1823, NAVIER, Mém. Acad. sci., v. 6, pp. 389ff	Derived general hydrodynamic equations for motion of viscous fluid. Integrated equations for flow through circular pipe: $U = C'D\Delta h/L$	Postulated slip with finite velocity at solid boundary resisted by proportional force. Introduced unnamed coeff. ϵ (equiv. to μ/ρ) Confirmed results of GIRARD.
1839, HAGEN, Ann. Phys. Chem., v. 46, pp. 423ff	Investigated pipe flow at low velocities: $Q = C'D^n\Delta h/L$ By least squares n = 4.12; adopted n = 4: $Q = C'D^4\Delta h/L$	Postulated zero slip, continuous velocity distribution. Departures from law ascribed to turbulence at low viscosities.
1842, POISEUILLE, C.-R. Acad. sci., v. 15, pp. 1167ff	Investigated flow of blood and other fluids in capillary tubes: $Q = C'D^4\Delta h/L$ Determined accurately the variation of water discharge with temperature: $Q/Q_o(=\nu_o/\nu)=1+0.0336T+0.000221T^2$	Observed thin stagnant layer of suspended matter at wall of capillary. Referred (in 1843) to HAGEN'S work.
1845, STOKES, Phil. Soc. Camb. Trans., v. 8, pp. 287ff	Derived NAVIER'S equations without recourse to molecular hypotheses. Integrated equations provisionally, assuming no slip, for flow through circular pipe: $Q = C'D^4\Delta h/L$	Used μ in place of NAVIER'S ϵ. Not then aware of the work of HAGEN or of POISEUILLE.

Table 1--Résumé of significant developments in connection with Darcy's law and the concept of permeability (continued)

Date and source	Contribution	Remarks
1854, DUPUIT, Traité de la conduite et de la distribution des eaux.		Anticipated DARCY'S law by analogical reasoning from results of POISEUILLE.
1856, DARCY, Les fontaines publiques de la ville de Dijon.	Investigated vertical flow of water through filter beds: $Q = kA\Delta h/L$ Described apparatus first used to determine k in the laboratory.	In DARCY'S own notation: $Q = ks(H + e)/e$, e being thickness of bed, s area of bed, H head measured above top of bed (discharging into atmosphere). k was designated variously as: "un coefficient dépendant de la nature du sable," ". . . du degré de perméabilité," ". . . . . de la perméabilité de la couche.."
1856, WIEDEMANN, Ann. Phys. Chem., v. 99, pp. 177ff		Introduced specific name Zähigkeit (viscosity) for coefficient in viscous-flow equations. Followed in this usage by HAGENBACH and by JACOBSON. MAXWELL later (in 1866) defined the "coefficient of viscosity," μ.
1880, SEELHEIM, Zs. Anal. Chem., v. 19	Investigated dependence of discharge (Durchlässigkeit) on head, flow length, area of cross section, temperature of water, and grain size: $Q=C'A\delta^2(\Delta h/L)(1+0.0136T+0.000704T^2)$	Term "Durchlässigkeit" (permeability) used in general sense to mean specific discharge. (In this equation, as in HAZEN'S, C' clearly has the dimension of (γ/μ) or $[1/LT]$.)
1892, HAZEN, Mass. Board Health, 24th Ann. Rep., pp. 541ff	Devised empirical formula for flow through filter sand: $Q = C'A\delta_e{}^2(\Delta h/L)(0.70 + 0.03T)$	δ_e denotes "effective size," than which ten per cent of the grains are smaller. C was found to vary with "uniformity coefficient," with shape of grains, and with porosity.
1899, SLICHTER, U. S. Geol. Surv., 19th Ann. Rep., Pt. 2, pp. 295ff	Analyzed flow through ideal homogeneous medium composed of spheres of uniform size, postulating an equivalent tortuous capillary of triangular section to which GREENHILL'S method is applied. Integration gives: $Q = (\rho g/\mu)(\delta^2/96K)A\Delta h/L = kA\cdot\Delta h/L$	In same report KING refers to SEELHEIM. Tables give viscosity of water for different temperatures, and values of the non-dimensional K for different porosities. "Transmission constant," k, defined as "the quantity of water that would be transmitted in unit time through a cylinder of the soil of unit length and unit cross section under unit difference in head at the ends."
1925, TERZAGHI, Eng. News-Rec., v. 95, pp. 832ff	$k = (C'\delta^2/\mu)[(\theta - 0.13)/(1 - \theta)^{1/3}]^2$	"k has been called the coefficient of permeability."
1925, UREN, Amer. Assoc. Petrol. Geol. Bull., v. 9, pp. 193ff	$Q = (C\delta^2\theta^{3.31}/\mu)A\cdot\Delta p/L$	SLICHTER'S (1/K) replaced by $\theta^{3.31}$.

Table 1--Résumé of significant developments in connection with Darcy's law and the concept of permeability (concluded)

Date and source	Contribution	Remarks
1927, KOZENY, Wien, Ak. Wiss. SitzBer., v. 136, Pt. 2a, pp. 271ff	$U = (\gamma/\mu)[C\delta^2\theta^3/(1 - \theta)^2]\cdot(\Delta h/L)$	As written here C includes KOZENY'S $1_s/1_w$, apparent/actual length.
1933, FAIR-HATCH, J. Amer. W. W. Assn., v. 25, pp. 1551ff	$U = (\gamma/\mu)[C\delta^2\theta^3/(1 - \theta)^2]\cdot(\Delta h/L)$	Except for length-ratio relation is same as KOZENY'S. Effective diameter determined from geometric means of size distributions for both stratified and unstratified beds.
1937, BAKHMETEFF-FEODOROFF, J. Appl. Mech., v. 59, pp. A97ff	$k = 2\gamma\delta^2\theta^{4/3}/C\mu$	For uniform spheres C found experimentally to be 710. Later, using deaerated water or air, C was found to be 640.
1943, KRUMBEIN-MONK, Trans. Amer. Inst. Min. Met. Eng., v. 151, pp. 153ff	$k = C\delta^2 e^{-a1\sigma_\phi}$	Experimented with artificially composed sands of fixed porosity (40%) having logarithmically normal size distributions. δ is geometric mean diameter; σ_ϕ is standard deviation.

through a cylinder of the soil of unit length and unit cross section under unit difference in head at the ends." This would appear to be the first specific term in the English language to be applied to the coefficient in DARCY'S equation.

Next we might consider the empirical expression by TERZAGHI for k as a function of the porosity. He regarded a porous medium to be simulated by a series of sieves, the minimal areas open to flow being one-fifth the maximal. If due allowance is made for the adjustment of the constants, TERZAGHI'S relation is found to follow SLICHTER'S very closely over the range of porosities from 35 to 50 per cent. Practically the same result was obtained by UREN, who replaced SLICHTER'S porosity function by the porosity raised to an appropriate irrational power.

Next came the equivalent expressions of KOZENY and of FAIR and HATCH, which were obtained independently. These give even greater variation of k with the porosity than does SLICHTER'S.

There might be mentioned also the work of SCHRIEVER [1930] and of HULBERT and FEBEN [1933]. SCHRIEVER found by experiment that $k \sim \delta^{1.68}$ and HULBERT and FEBEN got $k \sim \delta^{1.89}$. However, as far as establishing general relations, both of these expressions and all similar ones involving δ to an irrational power, are eliminated by dimensional considerations. Proceeding from DARCY'S equation and considering those factors that logically should go to make up k in geometrically similar systems, that is, the specific weight (driving force per unit volume at unity gradient) and the viscosity (resistive force per unit area per unit transverse velocity gradient) and the grain size of the sand

$$(Q/A)/(\Delta h/L) = k = C\gamma^x\mu^y\delta^z, \text{ or dimensionally}$$

$$(L/T) = (F/L^3)^x(FT/L^2)^y(L)^z$$

Equating exponents of T $\qquad -1 = y$

F $\qquad 0 = x + y; x = 1$

L $\qquad 1 = -3x - 2y + z; z = 2$

Whence

$$k = C\gamma\delta^2/\mu$$

In geometrically dissimilar systems C will vary with porosity, the shape and uniformity (or "grading") of the particles, their orientation and arrangement (homogeneous packing), and with whatever stratification there is on a larger scale (in nonhomogeneous material). In the writer's opinion the lines of attack that now seem most promising are those of BAKHMETEFF and FEODOROFF as regards porosity and those of KRUMBEIN and MONK as regards grading. A combination of methods suggested in both investigations will be needed in order properly to evaluate the influence of the particle shape of natural materials.

It remains for additional research over a wider range of porosity to verify further the expression involving porosity to the four-thirds power, which BAKHMETEFF and FEODOROFF deduced from dimensional reasoning. But, regardless of the eventual outcome of that research we may rely on the present unanimity regarding this proposition, that the product $C\delta^2$ in the foregoing equation characterizes the porous medium while the ratio μ/γ (or ν/g) characterizes the fluid and the external force field in which it flows. Clearly, if it be agreed that the word "permeability" ought to be reserved for that characteristic property of the porous medium, then $C\delta^2$ is the permeability. The writer feels that the word "permeability" ought to be so reserved, for there are good terms in use to describe the various other parameters to which the name "permeability" has sometimes been applied. Such of those terms as may not seem satisfactory might be replaced.

With regard to the expression "coefficient of permeability," the writer believes the first two words to be redundant here. It has been his observation that they have caused confusion, having been construed by some to establish the supposed non-dimensionality of that factor, which was regarded as the ratio between the permeability of a specified material and a standard unit of permeability. Actually, permeability is a physical property of a porous material just as density is, but in a physical sense it has only the subjective reality of the concept to which the measure of permeability K, of dimension L^2 is assigned. It was once customary, for example, to speak of the "coefficient of viscosity," whereas now we merely say "viscosity," meaning the same thing.

Before SLICHTER'S time k was generally referred to after the manner of DARCY. For instance, SMREKER wrote [1879], "k (ist) einen von der Durchlässigkeit und Beschaffenheit des Filtermaterials abhängigen constanten Coefficienten." However, SEELHEIM later used the word Durchlässigkeit (permeability) rather loosely to mean specific discharge. FOSSA-MANCINI wrote [1890], "k est un coefficient qui dépend du degré de permeabilité de la couche," again allowing for the implication that k depends also on other factors. It would appear that the first use of the expression "coefficient of permeability" with specific meaning was in a paper by WOLOGDINE, read before the London Congress of Applied Chemistry and translated from the French by QUENEAU [1909]. We read, "The coefficient of permeability v is the quantity of air in cubic centimeters passing under a head of one cm of water in one second through a cylinder of one sq cm cross section,and one cm in height." From that time on the terms "coefficient of permeability" and "permeability" were used rather loosely to apply to almost every conceivable combination of the factors involved, even to the reciprocal of the physical quantity itself [WOLF and GRUB, 1920]. Later TERZAGHI independently introduced the term "coefficient of permeability" into the American literature [1925]. In recent correspondence with the writer he states, "I heard this term for the first time some forty years ago from FORCHHEIMER, who at that time was my teacher. In his lectures on hydraulics he used the term 'Durchlässigkeitsziffer.' For some reason this term stuck to my memory and I myself was later responsible for introducing it into this country." The thing called "coefficient of permeability" by TERZAGHI is the same as the transmission constant of SLICHTER.

STEARNS [1927] included in her defining equation, relating the "coefficient of permeability" to discharge per unit area and to the hydraulic gradient, a temperature correction for the variation of the viscosity of the water. She stated, "The coefficient of permeability (in gpd/ft^2) of a material is the rate of flow in (standard U.S.) gallons a day, through a square foot of its cross section, under a hydraulic gradient of 100 per cent, at a temperature of 60° F." This "coefficient of permeability" again has the dimension L/T and is clearly the transmission constant corrected to a standard water temperature of 60° F. For, after STEARNS, a general definition of coefficient of permeability would be "rate of flow of water through a unit area of cross section, under a hydraulic gradient of 100 per cent, at a temperature of 60° F.

Table 2 lists the physical quantities involved in the alternate expressions of DARCY'S law for the flow of incompressible viscous liquids through porous materials. The question of symbols and notation deserves consideration. The writer has employed notation used quite generally in engineering hydraulics. The units of measurement shown comprise the American engineering system of units, in which the pound is the unit of force. Using the permeability, symbolized by K, DARCY'S law may be written so as to state that the "bulk" velocity (discharge per unit area) of a fluid of constant viscosity is the product of the gradient of the piezometric pressure (γh) and the ratio of the permeability to the viscosity (see last column of Table 2). By "piezometric pressures" are meant those pressures that would be recorded by gages situated at the same level. Piezometric pressure may be thought of as a pressure equivalent of head (in liquids) or as pressure corrected for elevation (in gases). The writer has suggested this term recognizing that only in horizontal flow is the velocity proportional to the pressure gradient, yet acknowledging the desirability of expressing DARCY'S law in the above form.

When the density also remains constant DARCY'S law may be expressed as $U=(\gamma K/\mu)\Delta h/L=k.\Delta h/L$, in which $k(=\gamma K/\mu)$ is SLICHTER'S transmission constant, corresponding to the coefficient in DARCY'S original equation. Objection has been raised to the transmission constant on the basis that it is not clear whether or not SLICHTER intended the temperature correction to be part of the transmission constant. But in his general definition, quoted in Table 1, no mention is made of a standard temperature. It is true that SLICHTER gave a table [U. S. Geological Survey, Water Supply Paper 140, Table II, p. 13] showing the "variation, with the temperature, of the flow of water of various temperatures through sand, 60° F being taken as the standard temperature." However, it is evident from the headings of Tables III and IV on page 15 of this Water-Supply Paper, wherein values of transmission constant are given for gravels at 80° F and for gravels at 72° F, that, as later pointed out by MEINZER [1923], "The transmission constant . . . is . . . . not the same for different temperatures; it is greater for high than for low temperatures." Further objection is often raised to the expression "transmission constant" by saying that it is not constant at all because it is a function of viscosity and density as well as of the structure of the material. In answer to this objection it need merely be stated that only when the viscosity, the density, and the other factors are constant is the transmission constant used as the constant in

Table 2--Physical quantities involved in the flow of incompressible viscous liquids through permeable media

Physical quantity	Symbol and defining equation	Dimension	F. p. s. unit	DARCY'S law
Elevation	z	L	ft	
Acceleration of gravity	g	L/T^2	ft/sec^2	
Specific weight	γ	F/L^3	lb/ft^3	
Density	$\rho = \gamma/g$	FT^2/L^4	$lb\ sec^2/ft^4$	
Pressure	$p = F/A$	F/L^2	lb/ft^2	
Head	$h = z + p/\gamma$	L	ft	
Potential	$\phi = gz + p/\rho$	L^2/T^2	ft^2/sec^2	
Piezometric pressure	$\gamma h = \gamma z + p$	F/L^2	lb/ft^2	
Viscosity	$\mu = \lambda/(\partial u/\partial y)$	FT/L^2	$lb\ sec/ft^2$	
Kinematic viscosity	$\nu = \mu/\rho$	L^2/T	ft^2/sec	
Permeability	$K = C\delta^2$	L^2	ft^2	$U = (K/\mu)\cdot\Delta(\gamma h)/L$ $= (\gamma K/\mu)\cdot\Delta h/L$
Transmission constant	$k = \gamma C\delta^2/\mu = gC\delta^2/\nu$	L/T	ft/sec	$U = k\cdot\Delta h/L$
Conductivity	$\sigma = \rho C\delta^2/\mu = C\delta^2/\nu$	T	sec	$U = \sigma\cdot\Delta\phi/L$ $= \sigma g\cdot\Delta h/L$

DARCY'S equation. Care must be taken to distinguish between absolute constants in a mathematical sense and constants as used in the equations of physics. Witness, for example, the "dielectric constant."

The conductivity parameter given in Table 2 was first suggested by ISRAELSEN and MORGAN [1937] under the name "specific water conductivity." (The word "specific" may be omitted, for conductivity is itself specific conductance, that is, the conductance of a specific cube of unit dimensions. Also, it is understood that we mean fluid conductivity or "water conductivity" in contrast to thermal conductivity and electrical conductivity.) The conductivity is a function of the kinematic viscosity as well as of the structure of the material. It has the dimension T. Perhaps it should be pointed out that BOUSSINESQ [1914] suggested the name "conductibilité" (conductivity) for the coefficient in DARCY'S original equation. But apparently no one has followed his suggestion. NUTTING [1927] proposed the name "conductivity" for the ratio K/μ, of dimension L^4/FT. Later [1930], however, he advocated "permeability" K, to be measured in units of (cm-centipoise/sec)/(megadyne/cm). His earlier suggestion has not been followed; hence we might regard the term "conductivity" as available for use as proposed by ISRAELSEN and MORGAN. HUBBERT [1940, p. 819] also advocates this term. RICHARDS [1940B] tentatively presented the same parameter under the name "permeability," suggesting the name "dar" for the unit (dar ≅ sec in cgs or fps units). Recently, EDLEFSEN and ANDERSON [1943] have given this factor the name "transmission function," apparently borrowing from SLICHTER'S "transmission constant," which, however, has the dimension L/T instead of T.

As to units of measurements, fluid conductivity may be measured in seconds, or perhaps more conveniently in microseconds. There should be no need of any other name for this simple unit. The microsecond may be used interchangeably in the metric and American systems; no conversion factors are involved.

The transmission constant k may be measured in whatever velocity units are practicable in a given field of activity. Because of the dimensional simplicity of velocity we do not need a distinctive name for the unit of that physical quantity. Nor should we find it necessary to coin a new name for the unit of transmission capacity or the transmission constant. As an all-around practical unit for field studies in ground-water hydraulics, where we are seldom concerned with absolute measures of permeability, the writer would suggest the ft/day, first because it is based on a consistent system of units, which avoids unnecessary conversion factors, and secondly because ordinarily the transmission constant in ft/day falls numerically within easy reach of the mind. The unit gpd/ft^2 employed by STEARNS and adopted by the Ground-Water Division of the Geological Survey is useful in water-supply work where discharge is reckoned in standard U. S. gallons per day. (The imperial gallon, used in Canada, is about 20 per cent larger.) However, in other ground-water work where water-supply systems are not involved, other units are more convenient, such as ft/sec. Other customary units are: in irrigation, ft/day; in infiltration studies, in/hr. As the hydraulic engineer must speak the language of those who use water, he must be familiar with different volumetric units. However, as a common denominator he has established the rational unit cubic foot, in terms of which each of the other units may easily be expressed. In line with the custom to use the foot instead of the centimeter as the fundamental length unit in American hydraulics laboratories, the ft/sec should, it would seem, replace the cm/sec as the laboratory unit of the transmission constant in this country.

The permeability K in rational fps units ft^2 usually is too small numerically to be quoted readily without the use of negative powers of ten. The same may be said also of permeability expressed in rational cgs units. The only advantage the latter has over the former is its flexibility, which the use of decimal prefixes allows. (Apparently the lexicographers still frown upon the idea of attaching Latin or Greek prefixes to "barbarian" roots.) This advantage will not help us, unless one wishes to express permeabilities in square microns. Even if we were to use square millimeters, we would still find negative powers of ten useful. This being the case, it would seem that until a universally acceptable permeability unit is adopted, engineers in this country might well express permeabilities in terms of the square foot.

This is one place where a new name for the unit eventually will be called for. And it remains to be decided first whether this unit is to be based on the metric system or on the English system, and secondly at what level of magnitude it is to be fixed so as to be convenient, for example, in ceramics as well as in ground-water hydraulics. We may find that if we attempt too much to honor practical considerations in these two decisions it will not be possible to establish any single unit that will be acceptable to everyone. Accordingly it may turn out that the rational units ft^2 and cm^2 will hold sway, the inconvenience of the very small numerical magnitudes being outweighed by the simplicity and adaptability of these units. (As a suggestion, the name "dar" proposed by RICHARDS would still appear to be available for the name of the universal permeability unit.)

Table 3 shows the relation between the various units discussed above for water at 60°F (kinematic viscosity 1.21×10^{-5} ft^2/sec) and at standard gravity (32.174 ft/sec^2).

Table 3--Comparison of numerical values of flow parameters for water at 60°F and at standard gravity

Parameter	Symbol	Unit	Numerical value			
Permeability	K	ft^2	1×10^{-12}	0.376×10^{-12}	4.35×10^{-12}	12.1×10^{-12}
Transmission constant	k	ft/sec	2.66×10^{-6}	1×10^{-6}	11.57×10^{-6}	32.17×10^{-6}
		ft/day	0.230	0.0864	1	2.78
		gpd/ft^2	1.72	0.646	7.48	20.8
Conductivity	σ	microsec	0.0826	0.0311	0.360	1

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APPENDIX E--LIST OF CURRENT PUBLICATIONS CONCERNING GROUND WATER

Jean M. Berdan

ALEXANDER, W. H., Jr., BROADHURST, W. L., and WHITE, W. N., Progress report on ground water in the High Plains in Texas, Tex. State Bd. Water Engrs., 12 pp., 7 figs. (mimeographed), May 1944.
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DISCUSSION OF

"THE VARIATION OF VORTICITY IN THE ATMOSPHERE"

BY EDWARD V. ASHBURN and LEONARD L. WEISS

[Trans., v. 26, pp. 205-211, 1945]

B. HAURWITZ (Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts) and **R. B. MONTGOMERY** (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts), December 13, 1945--The authors show that $f + \xi$, the vertical component of absolute vorticity on the rotating Earth, is not conservative if the absolute vorticity remains constant. If the vertical component of absolute vorticity is not conservative for inviscid barotropic flow without horizontal divergence, then the works of HAURWITZ and ROSSBY to which the authors refer would indeed be invalid. The paper under discussion is not, however, correct in its statement on page 206 that in the case "of an atmosphere composed of a barotropic inviscous fluid . . . the absolute vorticity would remain constant."

While it is true that in inviscid barotropic flow "vorticity can be neither created nor destroyed," and furthermore that the strength of any vortex is constant [LAMB, Hydrodynamics, 6th ed., p. 203], it follows that vorticity is conservative only in the special case that the vorticity is initially zero. It is helpful to remember that with inviscid barotropic flow the vortex-lines move with the fluid [LAMB, p. 204]; consequently it is easy to think of examples where the vortex-lines are deformed and the vorticity therefore changed in direction and magnitude, but of course neither created nor destroyed.

The vertical component of absolute vorticity on the rotating Earth is, in contrast to the authors' conclusions, conservative for inviscid barotropic flow without horizontal divergence. This conclusion does not depend on "the form of the equations of motion in which the curvature of the Earth is neglected." The necessary conditions are easily seen from BJERKNES' circulation theorem. For inviscid barotropic flow this may be written

$$dC/dt + 2\Omega dF/dt = 0$$

where dC/dt is the rate of change of the circulation relative to the Earth, Ω is the Earth's angular velocity, and F is the area enclosed by the curve's projection onto the equatorial plane. Integrating,

$$C + 2\Omega F = \text{constant}$$

Choosing a small horizontal curve enclosing an area s, the relative circulation is $C = s\xi$, where ξ is the vertical component of relative vorticity. Also $F = s \sin\varphi$, where φ is latitude, so $2\Omega F = 2\Omega s \sin\varphi \equiv sf$. Assuming no horizontal divergence, s is constant, and it therefore follows that

$$\xi + f = \text{constant}$$

These substitutions are permissible if the material curve chosen initially horizontal remains so. If the flow is horizontal, this condition is exactly fulfilled; for all large-scale features of atmospheric flow it is essentially fulfilled.

It should also be pointed out that in the first paragraph of the paper the statement of the last sentence is incomplete, because the "deformation of any fluid element" is not determined at all by the translation, divergence and vorticity, but is represented by another set of quantities entirely.

GEORGE E. FORSYTHE (1819 Hill Street, Ann Arbor, Michigan, March 1, 1946)--The authors have cited as a demonstrable principle of hydrodynamics a theorem which is not true. On page 206 the authors state: "It may be shown that in a non-viscous fluid in motion under the action of external forces which have a potential, and in which the density is constant or a function of the pressure only, that vorticity can be neither created nor destroyed." Their later text makes it clear that the authors are asserting that under their hypotheses the vector vorticity of a fluid particle does not change with time. This is of course a corruption of the famous HELMHOLTZ-BJERKNES theorem, which states that under the same hypotheses the circulation of a fixed chain of fluid particles cannot change.

Knowing the HELMHOLTZ-BJERKNES theorem, one can invoke a heuristic argument to see why the ASHBURN-WEISS statement cannot be true, even for two-dimensional flow. The vorticity is equal (in the limit) to the circulation around a small contour, divided by the area within the contour. If the contour is a chain of fluid particles within a region of divergence, the enclosed area must increase with time. Since the circulation remains constant, the vorticity decreases. In three-dimensional flow the vector vorticity can change even in the absence of divergence, if the orientation of the rotational axis of the fluid chain changes. A specific counter-example of the latter type will now be given.

Let X, Y, Z be an inertial Cartesian coordinate system, with unit vectors $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$. Let a fluid of constant density be in steady motion with the velocity at each point (x, y, z) given by

$$\mathbf{w} = \mathbf{w}(x,y,z) = (y \cos z - x \sin z)^2 \, (\mathbf{i} \cos z + \mathbf{j} \sin z)$$

Since each fluid particle is moving in a straight line (the line in the plane $Z = z$ passing through the point (x,y,z) with slope $(dY/dX = \tan z)$ at a uniform speed (a speed equal to the square of the perpendicular distance from the above line to the Z axis), it is under the action of no force. The flow therefore falls trivially under the hypotheses of the authors' purported theorem. The divergence can easily be computed to be identically zero. Now in the plane $Z = 0$ the vector velocity at the point $(x, y, 0)$ is given by the equation

$$\mathbf{w} = y^2 \, \mathbf{i}$$

In the same plane the vector vorticity is given by the equation

$$\boldsymbol{\zeta} = - y^2 \, \mathbf{i} - 2xy \, \mathbf{j} - 2y \, \mathbf{k}$$

Hence the time-rate of change of vector vorticity in the plane $Z = 0$ is found to be given by the equation

$$d\boldsymbol{\zeta}/dt = - 2y^3 \, \mathbf{j}$$

Thus the vector vorticity of the particles which are in the plane $Z = 0$, but not on the X axis, changes with time. This completes the demonstration of the counterexample.

The general equation for the time-rate of change of vector vorticity for the motion of a non-viscous fluid under the action of potential forces is essentially the last equation in the paper under discussion. Changed slightly so as to retain an inertial coordinate system, it says that

$$d\boldsymbol{\zeta}/dt = - (\nabla \cdot \mathbf{w})\boldsymbol{\zeta} + \boldsymbol{\zeta} \cdot \nabla \mathbf{w} - \nabla\alpha \times \nabla p \quad \ldots\ldots\ldots\ldots \quad (1)$$

For autobarotropic flow ($\nabla\alpha \times \nabla p \equiv 0$) it is seen from (1) that for a given, fixed-fluid particle, *either* $\boldsymbol{\zeta}$ is always zero; *or* $\boldsymbol{\zeta}$ is never zero (but its non-zero vector value may change with time). It is only in this much weakened sense that one may state that vorticity is neither created nor destroyed.

Once its basic principle has been shown fallacious, the paper under discussion loses its entire *raison d'être*. But since the issue has been opened, it may be worth while once more to prove ROSSBY'S equation for the rate of change of the component ζ_r of the absolute vorticity vector along the Earth's local vertical. (The variable ζ_r is the scalar absolute vorticity of meteorology, frequently denoted by $\zeta + f$ and called simply the "absolute vorticity.")

Let arbitrary curvilinear coordinates be given in an inertial system. Using notation $\mathbf{w}$ = the vector field of motion of a non-viscous compressible fluid subject only to potential forces, $\boldsymbol{\zeta}$ = absolute vector vorticity, α = specific volume, p = pressure, $\mathbf{d} = [(\nabla \cdot \mathbf{w})\,\boldsymbol{\zeta} + \nabla\alpha \times \nabla p]$, $\mathbf{a}$ = unit vector along one curvilinear coordinate, ζ_a, v_a, d_a, $(\nabla\alpha \times \nabla p)_a$ = the components along $\mathbf{a}$ of $\boldsymbol{\zeta}$, $\mathbf{w}$, $\mathbf{d}$, $\nabla\alpha \times \nabla p$, and let a superior dot stand for the material derivative d/dt taken with respect to the inertial system. Then it will be proved that

$$\dot{\zeta}_a = \boldsymbol{\zeta} \cdot \nabla v_a + \boldsymbol{\zeta} \cdot (\nabla_a \times \mathbf{a}) \times \mathbf{w} - (\nabla \cdot \mathbf{w})\,\zeta_a - (\nabla\alpha \times \nabla p)_a \quad \ldots\ldots\ldots\ldots \quad (2)$$

where we establish the convention that, in cases of ambiguity, the subscript on ∇ is the variable *on which* ∇ *operates.*

The following proof of (2) and derivation of the later equations are HOLMBOE'S, as communicated to the present writer in the autumn of 1945. They represent a more elegant demonstration of the facts known to the present writer when the paper under discussion was presented. The vorticity theorem (1) says that

$$\dot{\boldsymbol{\zeta}} = \boldsymbol{\zeta} \cdot \nabla \mathbf{w} - \mathbf{d} \quad \ldots\ldots\ldots\ldots (3)$$

Now since $\zeta_a = \boldsymbol{\zeta} \cdot \mathbf{a}$, we see that

$$\dot{\zeta}_a = \dot{\boldsymbol{\zeta}} \cdot \mathbf{a} + \dot{\mathbf{a}} \cdot \boldsymbol{\zeta} \quad \ldots\ldots\ldots\ldots (4)$$

From (3) we find that

$$\dot{\boldsymbol{\zeta}} \cdot \mathbf{a} = \boldsymbol{\zeta} \cdot \nabla_v \mathbf{w} \cdot \mathbf{a} - d_a$$

or

$$\dot{\boldsymbol{\zeta}} \cdot \mathbf{a} = \boldsymbol{\zeta} \cdot \nabla v_a - \boldsymbol{\zeta} \cdot \nabla_a \mathbf{a} \cdot \mathbf{w} - d_a \quad \ldots\ldots\ldots\ldots (5)$$

Since $\partial \mathbf{a}/\partial t = 0$,

$$\dot{\mathbf{a}} \cdot \boldsymbol{\zeta} = \mathbf{w} \cdot \nabla_a \mathbf{a} \cdot \boldsymbol{\zeta} \quad \ldots\ldots\ldots\ldots (6)$$

Substituting (5) and (6) into (4), we see that

$$\dot{\zeta}_a = \boldsymbol{\zeta} \cdot \nabla v_a + \boldsymbol{\zeta} \cdot (\mathbf{w} \cdot \nabla \mathbf{a} \cdot \nabla_a \mathbf{a} \cdot \mathbf{w}) \times \mathbf{w} - d_a$$

or

$$\dot{\zeta}_a = \boldsymbol{\zeta} \cdot \nabla v_a + \boldsymbol{\zeta} \cdot (\nabla_a \times \mathbf{a}) \times \mathbf{w} - d_a$$

The last equation is equivalent to (2), whose proof is thus completed.

Let the Earth be assumed spherical. For the absolute spherical coordinates λ, ϕ, r with the corresponding unit vectors $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, we have

$$\left\{ \begin{aligned} \nabla \times \mathbf{a} &= (1/r)\,\mathbf{b} + (1/r) \tan\phi\ \mathbf{c} \\ \nabla \times \mathbf{b} &= -(1/r)\ \mathbf{a} \\ \nabla \times \mathbf{c} &= 0 \end{aligned} \right\} \quad \ldots\ldots\ldots\ldots (7)$$

Let u, v, w be the corresponding spherical components of the absolute velocity $\mathbf{w}$. From (2) and (7) it follows that the spherical components of the vorticity theorem are as follows:

$$\begin{aligned} \dot{\zeta}_\lambda &= \boldsymbol{\zeta} \cdot \nabla u + (1/r)(w\zeta_\lambda - u\zeta_r) + (1/r) \tan\phi\ (u\zeta_\phi - v\zeta_\lambda) - (\nabla \cdot \mathbf{w})\zeta_\lambda - (\nabla\alpha \times \nabla p)_\lambda \\ \dot{\zeta}_\phi &= \boldsymbol{\zeta} \cdot \nabla v - (1/r)(v\zeta_r - w\zeta_\phi) - (\nabla \cdot \mathbf{w})\zeta_\phi - (\nabla\alpha \times \nabla p)_\phi \\ \dot{\zeta}_r &= \boldsymbol{\zeta} \cdot \nabla w - (\nabla \cdot \mathbf{w})\zeta_r - (\nabla\alpha \times \nabla p)_r \quad \ldots\ldots\ldots\ldots (8) \end{aligned}$$

The equation (8) is ROSSBY'S vorticity theorem. It is seen from it that ζ_r is a constant if the non-viscous flow of a fluid subject only to potential forces satisfies all the following conditions: (1) The quantity $(\nabla\alpha \times \nabla p)_r$ is zero; (2) the divergence $\nabla \cdot \mathbf{w}$ is zero; (3) the vertical motion w is zero. These are ROSSBY'S assumptions, and the invariance of ζ_r is his result. The same (potential) forces which keep the flow horizontal serve also to keep the scalar absolute vorticity constant. (See bottom of page 207 in paper under discussion.)

The writer concurs in the apparent wish of ASHBURN and WEISS that meteorologists would always use spherical coordinates explicitly. However, ASHBURN and WEISS (see the middle of their page 207) apparently fail to recognize that ROSSBY and other meteorologists frequently express equations and results in Cartesian coordinates for convenience, while basically using a spherical system. It would perhaps be best to express all equations in vector form, since vector expressions are independent of any coordinate system.

EDWARD V. ASHBURN and **LEONARD L. WEISS** (U. S. Weather Bureau, Washington, D. C., authors' closure)--In deriving his vorticity theorem, ROSSBY used a form of the equations of motion which, combined with the assumption that the terms $(\partial w/\partial y)(\partial u/\partial z)$, $(\partial w/\partial x)(\partial v/\partial z)$, and $2\Omega \cos\varphi (\partial w/\partial y)$ are negligible, implies the assumption of a flat Earth. In addition ROSSBY placed

$$(df/dy) = (2\Omega \cos\varphi/a) \quad \ldots\ldots\ldots\ldots (1)$$

(the nomenclature is that of ROSSBY)

In the system of coordinates that ROSSBY used the curl of $\mathbf{\Omega}$ is

$$\nabla \times \mathbf{\Omega} = [(\partial\Omega_z/\partial y) - (\partial\Omega_y/\partial z)]\,\mathbf{i} + [(\partial\Omega_x/\partial z) - (\partial\Omega_z/\partial x)]\,\mathbf{j} + [(\partial\Omega_y/\partial x) - (\partial\Omega_x/\partial y)\mathbf{k} = 0 \quad \ldots\ldots\ldots (2)$$

where $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ are unit vectors along x, y, z, respectively, since Ω is a constant vector.

It is obvious that $(\partial\Omega_y/\partial z) = 0$.

Therefore $(\partial\Omega_z/\partial y) = (\partial f/\partial y) = 0 \neq (2\Omega \cos\phi/a)$ .... (3)

Placing $(\partial f/\partial y) = 0$, ROSSBY'S vorticity theorem then becomes

$$(d\zeta/dt) = -(\zeta + f)(\partial u/\partial x) + (\partial v/\partial y) \quad \ldots\ldots\ldots (4)$$

instead of

$$d(\zeta + f)/dt = -(\zeta + f)(\partial u/\partial x) + (\partial v/\partial y) \quad \ldots\ldots\ldots (5)$$

Equation (4) is identical to the result given by PETTERSSEN (Weather Analysis and Forecasting, p. 232).

Our statement on page 206 of the paper under discussion that HAURWITZ, MONTGOMERY, and FORSYTHE have questioned, is incomplete. The authors' ideas are expanded and clarified in the paper mentioned at the end of this discussion.

We cannot agree that the equation (8) given by FORSYTHE and the derivation given by HAURWITZ and MONTGOMERY are equivalent to the vorticity theorem as derived by ROSSBY. The d/dt in ROSSBY'S theorem is the material derivative with respect to a coordinate system fixed to the Earth and not to a vertical moving with the fluid element.

If only the most significant terms in HELMHOLTZ' vorticity theorem are used, it may be of interest to point out that if the divergence in FORSYTHE'S equation (8) is expressed in spherical coordinates, then we get a term $2\Omega v/r \tan\phi \sin\phi$, which is larger than df/dt above 45° latitude.

Recently we have prepared, with R. D. ELLIOTT, a more nearly complete draft of a paper discussing the time rate of change of vorticity. The tentative draft of this paper is now being given limited distribution for comment.

DISCUSSION OF

"DIVERGENCE OF THE HORIZONTAL WIND" by NORMAN R. BEERS

[Trans., v. 26, pp. 226-236, 1945]

J. R. FULKS (U. S. Weather Bureau, Washington, D. C., June 6, 1945)--BEERS' method is valid if used under certain well-defined conditions, but it appears doubtful to me that these conditions can be met in actual practice.

He analyzes some of the simpler mathematical curves that can be used to represent stream lines of wind flow and determines $c\nabla \cdot t$, the divergence of the unit vector multiplied by the wind speed, for each of the curves. For a complete computation of divergence, it is necessary to also evaluate $t \cdot \nabla c$. If both $c\nabla \cdot t$ and $t \cdot \nabla c$ are evaluated the results should be valid, provided the determination is made from a wind field that is accurately known from direct observation.

The method is purely kinematical and results should be the same as if $(\partial u/\partial x) + (\partial v/\partial y)$ were evaluated. BEERS claims greater ease for his method, and this claim is supported partly by the fact that certain of the computations can be made once and for all. He states, however, [Section 3, p. 226] that the evaluation of $(\partial u/\partial x + \partial v/\partial y)$ is untrustworthy in practice; a statement which is true only because of inaccuracy or scarcity of the wind-data. Any other purely kinematical method, including BEERS', must be subject to the same uncertainty.

The author assumes that $t \cdot \nabla c$ may in many cases by neglected. In any case where $t \cdot \nabla c$ is definitely known to be negligible, the results should be valid, but an examination of wind data will show that there are nearly always changes in wind speed from station to station, and it would appear that evaluation of this term would be necessary even to determine the fact that it is not significant. Lacking statistical evidence to the contrary, synoptic experience would indicate that there are equally as many if not more cases where $t \cdot \nabla c$ would be more important as compared to $c\nabla \cdot t$.

It is difficult to reconcile BEERS' method with the result of studies described by BJERKNES and HOLMBOE in the reference cited by BEERS. The methods discussed by BJERKNES and HOLMBOE are based on a knowledge of a combination of physical, dynamical, and kinematical considerations, and do not require a knowledge of observed winds. The patterns of divergence for sinusoidal stream lines do not agree with BEERS' results, and the difference can perhaps be accounted for by the fact that BEERS neglects the term $t \cdot \nabla c$. This fact would argue against eliminating $t \cdot \nabla c$ from consideration, since it appears to be of obvious importance in the BJERKNES-HOLMBOE analysis.

BEERS suggests using isobars (or isohypses) for determining the stream lines. For a complete determination of convergence by kinematical methods, it is necessary to take into account all the dynamical and physical factors that enter into a determination of the wind field. This would be comparatively simple if geostrophic or gradient conditions are assumed, but we have good reason to believe that convergence and divergence in the atmosphere are to no small extent associated with departures of the wind from true geostrophic or gradient winds. To obtain true winds, a knowledge of accelerations is required, and these depend not only on static forces (such as the pressure gradient) and their changes, but also on the initial winds at any given time. BJERKNES and HOLMBOE consider accelerations only qualitatively, but their analysis takes into account all the divergence due to strictly gradient flow. It therefore appears preferable that divergence, if it is to be based on pressure gradients (horizontal), be determined by the methods described by BJERKNES and HOLMBOE rather than by attempting to first compute the winds and then applying kinematical methods. It might be argued that BEERS' method requires knowing only the stream lines accurately, but this argument can be accepted only if it is determined that $t \cdot \nabla c$ is negligible.

R. D. ELLIOTT (U. S. Navy Long Range Forecast Unit, U. S. Weather Bureau, Washington, D. C., June 22, 1945]--In some of the fields presented the horizontal divergence must be zero. In the following discussion this is shown to be true for Case III.

In Case III for stream lines: $(x^2/a^2 + y^2/b^2) = 1$; $f = -(b^2x/a^2y)$. We know $u = -a^2y$ and $v = b^2x$. According to the paper, $t = i(u/c) + j(v/c) + k(0)$. Also $c = \sqrt{u^2 + v^2} = \sqrt{a^4y^2 + b^4x^2}$ and $\nabla c = i(b^4x/c) + j(a^4y/c)$.

Therefore $t \cdot \nabla c = [i(u/c) + j(v/c)] \cdot [i(b^4x/c) + j(a^4y/c)$

$$= (b^4 ux + a^4 vy)/c = [b^4(-a^2y)x + a^4(b^2x)y]/c$$

$$= (a^2 - b^2) b^2 a^2 x y/c = -(a^2 - b^2) vu/(a^4y^2 + b^4x^2)$$

which is equal and opposite in sign to the value BEERS finds for $c \cdot \nabla t$.

Therefore $c \cdot \nabla t + t \cdot \nabla c = \nabla \cdot V = 0$.

CHARLES S. GILMAN (Weather Bureau Airport Station, Hialeah, Florida, February 25, 1946)--Physical picture: A physical picture of the two parts of horizontal divergence discussed in BEERS' paper is as follows: $t \cdot \nabla c = (\partial c/\partial t)$, where t is the unit vector along the direction of the wind--not time; that is, the change of wind speed along the stream line. If the speed decreases along the stream line, there is convergence, while, if it increases, there is divergence (see Fig. 1).

To evaluate, $c\nabla \cdot t$, choose a point O, at which to study the divergence and let the value of t at O be t_0. Then choose another unit vector at O normal to and to the left of t_0, say n_0. At any other point of the field $t = t_0 \cos \alpha + n_0 \sin \alpha$ and $\nabla \cdot t = -\sin\alpha(\partial\alpha/\partial t) + \cos\alpha(\partial\alpha/\partial n)$, where α is the angle between t and t_0.

At the point, O, however, $\alpha = 0$, $\sin\alpha = 0$, $\cos\alpha = 1$. Therefore $\nabla \cdot t = (\partial\alpha/\partial n)$ at the point, O.

$(\partial\alpha/\partial n)$ is, of course, $(1/r_0)$ where r_0 is the radius of curvature of the orthogonal trajectory of the stream lines. If the orthogonal trajectory is concave toward the direction from which the wind blows, there is divergence, while, if it is concave toward the direction to which the wind blows, there is convergence (see Fig. 2).

This result is readily applied to the examples in BEERS' paper. For example, the orthogonal trajectories of the parallel straight lines shown in BEERS' Figure 4 are straight lines with infinite radius of curvature, and $c\nabla \cdot t = c/\infty = 0$ as given in equation (13).

Again, the orthogonal trajectories of the straight lines radiating from the origin in BEERS' Figure 5 are circles concentric at the origin, and $c\nabla \cdot t = (c/r)$. This is the equivalent of equation (14) where r is the distance from the origin, that is, the radius of a circle whose center is at the origin.

If we consider next the case of the ellipses with constant eccentricity, the equation of an ellipse is $x^2/a^2 + y^2/b^2 = 1$. Its slope at any point is $(dx/dy) = -(x/y)(b^2/a^2) = -(x/y)(1/\epsilon^2)$ and the slope of the orthogonal trajectory is at any point the negative reciprocal or $(dy/dx)_{ot} = (y/x)\epsilon^2$. Integration gives $y = kx^{\epsilon^2}$, where k is the constant of integration. That is, the orthogonal trajectories of the family of ellipses constitute a family of exponential curves. Figure 3 shows two curves of this family.

The radius of curvature of these orthogonal trajectories is given by $(1/r_o) = (d^2y/dx^2)/[1 + (dy/dx)^2]^{3/2}$. But $d^2y/dx^2 = (dy/dx)\epsilon^2/x - (y/x^2)\epsilon^2 = (y/x^2)\epsilon^2(\epsilon^2 - 1)$, and $(1/r_o) = [(y/x^2)\epsilon^2(\epsilon^2 - 1)]/(1 + y^2/x^2)^{3/2}$

Now the direction of curvature of the exponential curves is given by the numerator of this expression, $(d^2y/dx^2) = (y/x^2)\epsilon^2(\epsilon^2 - 1)$, and if $\epsilon > 1$, the curvature has the same sign that y has. That is, the curve is concave upward above the x-axis and concave downward below the x-axis. More the slope of the trajectory, $(y/x)\epsilon^2$, is positive in quadrants I and III and negative in quadrants II and IV. Therefore the orthogonal trajectories are always concave toward the y-axis. Whence the conclusions of BEERS regarding convergence and divergence follow immediately--for example, for clockwise (anticyclonic) flow, there is divergence in quadrants I and III, and convergence in quadrants II and IV.

Similarly, for a family of hyperbolas with common eccentricity, $(x^2/a^2) - (y^2/b^2) = 1$, and the slope at any point is $(dy/dx) = (x/y)a^2/b^2 = (x/y)1/\epsilon^2$. Therefore the slope of the orthogonal trajectory is $(dy/dx)_{ot} = -(y/x)\epsilon^2$. Integration gives $y = kx^{-\epsilon^2}$, where k is the constant of integration.

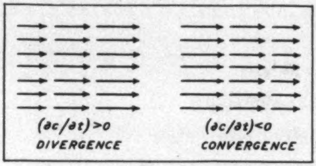

Fig. 1

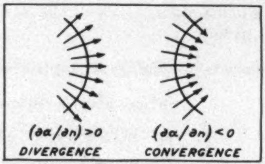
$(\partial \alpha/\partial n) > 0$
DIVERGENCE
$(\partial \alpha/\partial n) < 0$
CONVERGENCE

Fig. 2

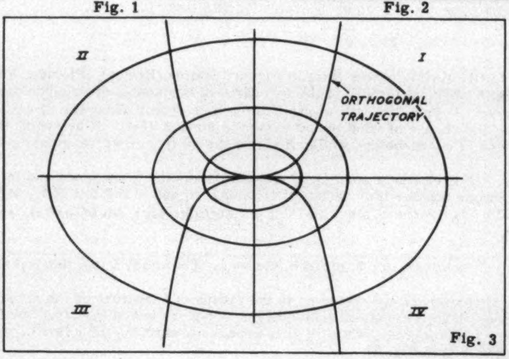

Fig. 3

The sign of curvature is given by $(d^2y/dx^2) = [d(-y/x)\epsilon^2/dx] = (y/x^2)\epsilon^2(\epsilon^2 - 1)$.

Again, for $\epsilon > 1$, the curves are concave upward above the x-axis and concave downward below the x-axis. However, the slope of the orthogonal trajectories, $-(y/x)\epsilon^2$, is now positive in quadrants II and IV and negative in quadrants I and III. Therefore, the orthogonal trajectories are everywhere concave toward the x-axis, and BEERS' conclusions regarding convergence and divergence follow at once.

Consider next the family of sine curves with common wave length and amplitude discussed by BEERS in Case IV. The slope of any curve of the family is given by $(dy/dx) = A(2\pi/L)(\cos 2\pi x/L)$.

The negative reciprocal is $(dy/dx)_{ot} = -(L/2\pi A)\sec(2\pi x/L)$. The second derivative of the orthogonal trajectory is $(d^2y/dx^2)_{ot} = -(1/A)\tan(2\pi x/L)\sec(2\pi x/L)$.

The curvature of the orthogonal trajectories is $-(1/A)\sin(2\pi x/L)/\cos(2\pi x/L)/[1 - (L^2/4\pi^2A^2)\sec^2(2\pi x/L)]^{3/2}$.

Criticism of method: That BEERS used only kinematic methods in arriving at the result that directional convergence or divergence depends on the increasing or decreasing curvature of the stream lines is extremely interesting. Similar results for isobars and trajectories followed from application of the equations of motion by BJERKNES [1937, see "References" at end of discussion], PETTERSSEN [1940], and GILMAN [1943]. An important difference, however, is that for sinusoidal waves, previous studies indicated convergence for the entire distance from wedge line to trough line proceeding down stream and divergence for the entire distance from trough line to ridge.

Of course, BEERS' method, as he points out, has the following weaknesses: (1) That he treats only very special cases--for example, concentric ellipses of uniform eccentricity; and (2) that he fails to show the interrelationship of speed- and directional-divergence.

Concerning the first weakness, it is not difficult to find a case where the occurrence of convergence or divergence may be reversed from that given by the increase or decrease of curvature of the stream lines. For example, the second derivative of the orthogonal trajectories of a family of concentric ellipses with variable eccentricity is $(d^2y/dx^2) = d(\epsilon^2 y/x)\,dx = \epsilon(y/x)[(\epsilon/x)(\epsilon^2 - 1) + 2\,d\epsilon/dx]$.

The condition that this second derivative vanish, (except along the axes) is $(\epsilon/x)(\epsilon^2 - 1) + 2d\epsilon/dx = 0$, or $(d\epsilon/dx) = -(\epsilon/x)(\epsilon^2 - 1)/2$.

Obviously, when this condition is fulfilled, the orthogonal trajectories are straight lines. If the rate of change of eccentricity with respect to x exceeds this, then the sign of the second derivative changes and the occurrence of divergence or convergence is reversed. The possibility and probability of such families is worthy of study.

The obvious conclusion is that the critical criterion of the occurrence of directional divergence and convergence is not the curvature of the stream-lines but the curvature of the orthogonal trajectory of the stream lines--not the curvature *along*, but the curvature *across* the stream lines. This curvature of the orthogonal trajectory should be a function of the curvature of the stream lines and of the gradient.

Concerning the second weakness, our synoptic experience indicates that in general the directional- and speed parts of horizontal divergence tend to cancel each other. That is, if the stream lines spread out, as shown in the first part of Figure 2, the speed decreases; so that the directional divergence is accompanied by speed convergence. And if the stream lines come together as shown in the second part of Figure 2, the speed decreases; so that directional convergence is accompanied by speed divergence. To what extent either the speed or directional part can exist without the others cancelling it is a question most pertinent--but, unfortunately, one which must go beyond kinematical methods to dynamics or to empirical evidence for its answer.

Whatever may be the criticisms of BEERS' method, the similarity of his results to those of PETTERSSEN and of this writer seems to show the soundness of the general method of attack and to encourage the hope that valuable results will follow its further pursuance.

References

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GILMAN, C., Excessive precipitation produced by convergence, Mass. Inst. Tech., Cambridge, Mass., 1943.

PETTERSSEN, S., Weather analysis and forecasting, McGraw-Hill, New York and London, p. 228, 1940.

NORMAN R. BEERS (U. S. Naval Academy, Annapolis, Maryland; author's closure)--FULKS' thoughtful review of my paper reiterates my emphasis that the method is valid if used under certain conditions, and that the method is kinematical. One might as well write that the method is direct rather than indirect, since the scalar quantity divergence is purely kinematical at a fixed instant of time. In partial explanation of my basic position respecting this paper I quote from an old teacher, A. E. H. LOVE, who writes: "In the process of formulation the science acquires the character of an abstract logical theory, in which all that is assumed is suggested by experience, all that is found is proved by reasoning. The test of the validity of a theory of this kind is its consistency with itself; the test of its value is its ability to furnish rules under which natural events actually fall."

On the basis of experience I assumed the stream line field could be represented by certain simple sets of curves. This is the only assumption of the paper. Using it and the identity $(c\nabla\cdot t + t\cdot\nabla c) = (\partial u/\partial x) + (\partial v/\partial y)$ I evaluated the term $c\nabla\cdot t$ for some special cases. These results are either rigorously correct or my mathematics is in error, typographical or otherwise, and FULKS does not suggest an error in the mathematics. I conclude that he agrees with me the paper is internally consistent and consequently valid in LOVE'S use of the word.

Whether or not the paper's results are valuable is another question entirely. In my experience they are; I infer they are not in the experience of FULKS. There are several possible explanations of his dissatisfaction with the paper, among which his implication that I intend the term $t\cdot\nabla c$ to be considered negligible in general must be prominent. That I neither had nor have such intent I repeat, though the statement is featured throughout the paper in words and in the caption of all appropriate figures. In my experience $t\cdot\nabla c$ is generally negligible in cases followed by pronounced storms and dynamic anticyclones (as indicated in my paper); but in practice the analyst must obviously determine it at least qualitatively. In addition, in my paragraph 5, I showed where a certain flow pattern gave $t\cdot\nabla c$ to be rigorously zero so that the horizontal divergence is then rigorously $c\nabla\cdot t$, but even in that paragraph I state that one must in general evaluate both terms.

Statistical results will of course be needed to indicate what probability attaches to conclusions drawn from any partial analysis. I have gone on record elsewhere with the statement, "it is considered improbable that any single index can be found from which one can correctly forecast." This applies equally well to the problem of forecasting surface pressure tendencies, and the divergence must be determined at several levels before one applies the result with confidence. The procedures for such an analysis require a fair amount of time with any method; my paper suggests a method whereby nomograms can be prepared in advance and used in seconds to find quantitatively $c\nabla\cdot t$ at any point in the observed wind field. If the actual stream-lines are any one of the sets of curves for which the nomograms have been prepared, and if the curves are correctly recognized, the nomogram gives $c\nabla\cdot t$. If one then computes the simpler term $t\cdot\nabla c$ and adds the two he has the correct horizontal divergence. The only chance for mistake is in a failure to recognize the curves, aside of course from errors that may exist in determination of the wind field.

As FULKS suggests, the results are precisely the same whether one evaluates $(c\nabla\cdot t + t\cdot\nabla c)$ or the equivalent $[(\partial u/\partial x) + (\partial v/\partial y)]$, or again the equivalent and well known expression $[(\partial c/\partial s) + c(\partial\alpha/\partial n)]$. My claim to faster analysis using $(c\nabla\cdot t + t\cdot\nabla c)$ is based on the reason given above, the preliminary construction of nomograms. Theoretically there is another important difference that becomes apparent when one notes that in general $c\nabla\cdot t$ and $t\cdot\nabla c$ are not separately equal to either $(\partial u/\partial x)$ or $(\partial v/\partial y)$.

Unlike FULKS I have no difficulty in reconciling the mathematics of my paper with the one cited by BJERKNES and HOLMBOE. There is no real basis for comparison of the two papers except by their use in weather forecasting; for BJERKNES and HOLMBOE discuss the divergence of the vector field ρv, while I discuss the divergence of the wind only. If the assumptions made in the two papers are applicable to the real atmosphere, then the two methods must give the same results when all the terms are taken into account, and either one could be preferred over the other only in so far as it proved to be simpler and/or faster in application to arbitrary weather situations. In my opinion neither method can be reduced to a single index, at a single level, that will permit a correct forecast all the time.

My suggestion that, in the absence of adequately accurate or numerous wind observations, one use the isobars or isohypses to judge the type of stream lines present was and is meant as an expedient only. The only use made of this expedient is to locate regions of pronounced divergence or convergence, and here it seems to work satisfactorily. In any case the scalar divergence is determined at a fixed time by the wind field at that time. If that wind field can be measured as accurately as we please then the divergence can be determined as accurately as we please for the time of the map. In this respect divergence is observable, that is, it can be computed exactly from the wind field which is observable. When this truth is generally recognized it is probable in my opinion that at least in selected regions accurate wind observations will be made.

I infer from the mathematics offered by ELLIOTT that he is suggesting the truth of his statement by showing it to be true in one special case. Elementary logic teaches that such a procedure is inadmissible. Actually the elliptical stream lines under discussion are given in general by the vector field $u = -a^2y/G(x,y,z,t)$, $v = b^2x/G(x,y,z,t)$, where $G(x,y,z,t)$ is an arbitrary non-zero function of the four independent variables x,y,z,t. In his differentiation ELLIOTT has considered the special case where the function G is identically unity and, as he shows, in this special case the divergence is indeed zero, a result that in fact is immediately evident by direct differentiation in the defining equation $\operatorname{div} v = (\partial u/\partial x) + (\partial v/\partial y)$ for the special case where $G(x,y,z,t) \equiv 1$, or any other constant (non-zero). In general $(\partial u/\partial x) + (\partial v/\partial y) \neq 0$ in my Case III.

GILMAN'S discussion is so obviously the sort of comment an author would like that I am going to say very little in reply. His introduction of orthogonal trajectories of the stream lines into the problem of horizontal divergence clarifies the truth that it is only a family of stream lines that has divergence, that is, $\nabla \cdot v$ is not defined for one curve. I had avoided all use of the word trajectory save the meteorologically common one (a curve that shows how one particle travels at every instant), because it is stream lines or approximations to stream lines that are easily drawn on synoptic maps. Nothing but good can result from the additional discussion, provided there is no confusion among stream lines, trajectories, and orthogonal trajectories of stream lines. It might be noted that trajectories also have orthogonal trajectories.

The second part of GILMAN'S discussion points up the things that must be examined carefully in any practical application. In particular it is in accord with my paper that one must determine both parts of the expression given for horizontal divergence. My suggestion is that success should attend the kinematic approach when accurate observations of wind (aloft) are available, for here essentially one assumption only need be made, that is, the nature of the stream-lines, whereas in the dynamic approach using the equations of motion one must assume the isobars or isohypses, and the motion of the systems, and then finally simplify in practice to gradient wind conditions before the equations are mathematically tractable.

DISCUSSION OF

"APPLICATION OF STATISTICAL THEORY TO MEASUREMENTS OF VELOCITY AND SUSPENDED SEDIMENT IN RIVERS"

BY A. A. KALINSKE

[Trans., v. 26, pp. 261-265, 1945]

A. A. KALINSKE (University of Minnesota, Minneapolis, Minnesota, author's closure)--In their discussions of this paper L. G. STRAUB and A. G. ANDERSON point out, very properly, that the analysis presented by the author relating to the time required for measuring velocity or suspended sediment is the time necessary to average out the fluctuations due to the turbulence. Other factors such as for instance human errors in observation are, of course, not considered; also, it is assumed that the meter or sampler employed is capable of obtaining the true mean value if the observations are made over a long enough period of time. In other words, the assumption is made that the current meter used measures the correct axial component, at any instant, of the velocity of the water, and that a suspended sediment sampler obtains, at any instant, a correct sample of the sediment in the water. Any errors inherent in the design of such instruments are, of course, not considered in the analysis. In any case, the time of measurement must be at least as long as that calculated from the author's analysis if the desired accuracy is to be secured.

Published data relating to the influence of velocity fluctuations on the accuracy of current meter measurements of velocity in rivers is rare indeed. It is hoped that the United States Geological Survey in connection with its river-flow measurements may have an opportunity to check the author's analysis.

In regard to suspended sediment sampling the equations given in the paper can be used to indicate the maximum accuracy that can be expected from samplers which take a sample of water for only a very short interval. How this accuracy varies for the various sediment sizes can be easily calculated by use of Equation (13) in the paper. As STRAUB points out in his discussion, in general, suspended sediments smaller than 1/16 mm do not vary greatly in concentration with time; however, it should be noted that the velocity of flow is a very important factor in this problem. Thus, for instance, for a given size of sediment and depth of river, for comparable accuracy, the sampling time in a river with a mean velocity of three ft per sec must be eight times as long as in a river with a mean velocity of six ft per sec.

DISCUSSION OF

"AN ACCOUNTING OF THE DAILY ACCRETION, DEPLETION, AND STORAGE OF SOIL-WATER AS DETERMINED BY WEIGHING MONOLITH LYSIMETERS"

BY L. L. HARROLD and F. R. DREIBELBIS

[Trans., v. 26, pp. 283-297, 1945]

L. L. HARROLD and F. R. DREIBELBIS (Soil Conservation Service, Coshocton, Ohio, authors' closure)--THORNTHWAITE'S initial conclusion that the measurements of percolation from the Coshocton lysimeters are most unreliable is based on the studies of NEAL, RICHARDS, and RUSSELL [see 3 of "References" in THORNTHWAITE'S discussion in Trans. Amer. Geophys. Union, v. 26, p. 297, 1945], and of WALLIHAN [9]. It would be well for those interested in this subject to note that the lysimeters in the former study were 36 inches deep on a gravel base and those in the latter study were 30 inches deep and 12 inches in diameter. The latter were of the filled-in type. THORNTHWAITE points out that where a tension of 136 cm of water was applied, the volume of percolation was five times greater, but did not state that this was the maximum difference on a fallow soil starting from the initial wetting, and that afterwards the difference was only about two times instead of five.

It is not known why THORNTHWAITE referred to COLMAN'S works [10] where the moisture in a soil column seven inches in diameter and six feet long was reduced to a level below field-capacity by a tension of 150 cm of water, unless it was to imply that where this tension exists in natural field-conditions the moisture is always below field capacity. THORNTHWAITE in his discussion states that "COLMAN'S conclusion would apply to the measurements of percolation of the lysimeters at Coshocton as well as to any others." It is interesting to observe that COLMAN [10] in the same article quoted by THORNTHWAITE states that "the soil water cycle in one type of lysimeter is not related with any degree of assurance to the cycle in any other kind. These findings indicate that serious difficulties may be encountered in any lysimeter study of vegetation water economy if an attempt is made to compare results from lysimeters of different depth or type since the findings might be influenced by the characteristics of the lysimeters themselves."

The authors believe that the data in the references cited by THORNTHWAITE do not necessarily apply to the Coshocton lysimeters where the profile depth is eight feet and the lower section of which consists of undecomposed bed rock. In the bed-rock sections of the lysimeters as well as over the sandstone and shale areas of Ohio, there are numerous cracks which naturally tend to break up any capillary tension from below.

THORNTHWAITE concluded tnat our values of percolation are too small and therefore the soil-moisture in the lysimeters was greater than in the surrounding areas, and the resulting values of evapotranspiration unnaturally high. This conclusion is unwarranted and could not be reached from the data in the paper, as actual changes in soil moisture determined from auger samples in the surrounding areas were comparable with those in the lysimeter, as shown in Table 1.

Table 1--Comparative data on changes in soil moisture

Date	Soil-moisture depth 0 to 40 inches		Weight	Change of weight	
	Amount	Change			
	inch	inch	pound	pound	inch
1943	Watershed 123			Lysimeter Y 103	
Aug. 12	11.23	. . . . .	2546.8	. . . . .	. . . .
31	9.75	- 1.48	1961.2	- 585.6	- 1.28
Sep. 3	9.06	- 0.69	1738.2	- 223.0	- 0.49
Oct. 11	8.27	- 0.79	1232.7	- 505.5	- 1.11
Total	. . . .	- 2.96	. . . . .	. . . . .	- 2.88
1944	Watershed 109			Lysimeter Y 102	
May 23	9.33	. . . . .	2883.2	. . . . .	. . . .
June 9	8.00	- 1.33	2014.2	- 869.0	- 1.91
July 7	6.69	- 1.31	1607.7	- 406.5	- 0.89
Aug. 11	5.49	- 1.20	957.5	- 650.2	- 1.43
Total	. . . .	- 3.84	. . . . .	. . . . .	- 4.23

The periods necessarily selected for this comparison were those when there was no percolation as it is probable that all the moisture changes as recorded by the lysimeter were caused by evapotranspiration and, therefore, took place largely in the section of the soil profile above the 40-inch depth.

THORNTHWAITE suggests the comparison of the lysimeter surface runoff plus percolation with runoff from natural drainage basins and brings into this discussion some of his computations of evapotranspiration using records of temperature and precipitation from a single Weather Bureau station. The authors are not familiar with this new method and believe that this is not the place to discuss at length such a procedure. The authors' closing discussion is merely to present data relating to the original paper.

In 1943 and 1944, both years of deficient rainfall, the total lysimeter runoff plus percolation was less than the runoff from Watershed 97 of 4580 acres in area. The runoff as measured at this station includes surface runoff as well as seepage flow. In 1943 the total runoff was about five inches more than the lysimeter runoff plus percolation. This is a natural phenomenon and can be readily explained. The ground-water table over the entire State lowered materially during these two dry years, and the runoff in the larger streams included some water that had percolated to the ground-water reservoir some years before. A reversal of this must also occur, as in 1941 when the total lysimeter runoff plus percolation totaled about 15 inches, whereas, the runoff measured at Station 97 (4580 acres) totaled only ten inches. In this year some water went into the ground-water reservoir and did not get into the larger rivers that same year.

In some months there is no percolation and no surface runoff from the lysimeters, yet there is continuous flow in the larger rivers. It seems erroneous to conclude that the lysimeter measurements of percolation and evapotranspiration are unreliable merely because these values, along with surface flow, do not balance each month or each year. Moreover, it seems quite logical to conclude that one should not expect these values to balance, except perhaps occasionally when the underground storage of water is the same at both the beginning and end of the measured period.

The authors conclude that the Coshocton lysimeter records (actual measurements) furnish the most reliable hydrologic data of this sort that have yet been acquired, either by actual measurements or by theoretical formulas.

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LETTERS TO THE EDITOR

DIVISION OF OCEANOGRAPHY ESTABLISHED IN THE HYDROGRAPHIC OFFICE, UNITED STATES NAVY

The Hydrographic Office has established a Division of Oceanography to provide for increased responsibilities in oceanography recently assigned to the Office by the Secretary of the Navy.

Because of experience during the war, the Navy considers that a considerable expansion of our knowledge of the oceans is necessary to guide the development of new naval equipment and to aid in strategic and tactical planning. Such an improvement in our understanding of the oceans will require a great increase in fundamental oceanographic research. This is true because our present basic oceanographic knowledge has been extended to the limit in its practical application during the war. In addition, new oceanographic techniques have opened many new possibilities of further fundamental investigations.

It is believed that such basic oceanographic research should be of value not only to the Navy, but also to many other governmental activities interested in the oceans, their land and air borders, and the organisms living in the sea, as well as to scientific institutions and to various commercial interests. For example, the increase in air travel over water has given increased emphasis to problems of maritime meteorology and air-sea rescue, requiring a knowledge of ocean currents. The extension of United States responsibility to regions of the western Pacific has greatly added to the national interest in geophysical and other problems of those areas, of which oceanographic problems are an integral part. Development of new fisheries and conservation of existing fisheries resources may in the future depend more and more on better oceanographic knowledge.

By expanding its oceanographic work, the Hydrographic Office will be continuing its tradition of service to the mariner and will afford other agencies a facility for coordination of oceanographic observations and research. The Hydrographer intends to maintain a central oceanographic library, central files of oceanographic data (to be published in a special bulletin), and a bibliographic service, and to provide charts and manuals utilizing the results of the most recent research. In carrying out this work, the Hydrographic Office will not only make use of the services of its own personnel in the newly established Division of Oceanography, but also will give financial support to oceanographic institutions to permit them to expand their facilities for basic research of interest to the Navy and other governmental agencies. In addition to publications of immediate practical use to mariners, the Hydrographer proposes to publish a series of technical studies which will be of interest to those working in applied oceanography as well as to personnel at research institutions not only in the United States but also abroad.

To insure an organization most useful to the Government and the maritime interests of the Nation, an Advisory Committee consisting of representatives of interested activities in the Navy and other Government agencies is being formed to advise the Hydrographer concerning oceanographic problems of special interest to the agencies represented, to assist in coordinating governmental research in oceanography, and to give continuing endorsement to the program. Cooperation of this sort should prove to be a most economical means of furthering the oceanographic interests of the country.

R. O. GLOVER
Rear Admiral, U. S. N.
Hydrographer

Hydrographic Office
Navy Department
Washington, D. C., March 11, 1946

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

FRIEDKIN, J. F.: A laboratory study of the meandering of alluvial rivers, U. S. Waterways Experiment Station, Vicksburg, Miss., 40 pp., 61 pls., May 1945.

Meandering is caused primarily by local bank erosion and consequent local overloading and deposition by the river of the heavier sediments which move along the bed. Meandering is essentially a natural trading process of sediments from banks to bars. Sand entering at the head of an alluvial river travels only a short distance before it deposits on bars along the inside of bends and is replaced by sand eroding from concave banks. In turn the sand from the caving banks of a bend travels only a short distance before it deposits on bars and is replaced by sand from caving banks. The rate of trading depends upon the rate of bank caving. In uniform materials and on a uniform slope, a series of uniform bends will develop. The radii of bends increase with increase in discharge or slope for the same alignment of flow into the bends. For the same flow and slope, the size and shape of bends depend upon the alignment of the flow into the bends. Cross sections of a meandering river are deeper along the concave banks of bends because of the impingement of the flow against these banks. The depth of the channel of a meandering river depends upon the resistance of the banks to erosion. Resistant banks result in deep cross sections and easily eroded banks result in shallow cross sections. Every phase of meandering represents a changing relationship between three closely related variables: The flow and the hydraulic properties of the channel, the amount of sand moving along the bed, and the rate of bank erosion. These three variables constantly strive to reach a balance but never do even with a constant rate of flow. The bends of a meandering river have limiting widths and lengths. When a bend reaches this width, a chute forms and a new bend develops farther downstream. Distorted bends and natural cut-offs are caused by local changes in the character of bank materials.

Observation of the behavior of a small-scale river as it began to meander showed that a local disturbance to the flow was created by a sand bar which resulted from bank erosion. Sand from caving banks overloaded the stream, and deposition took place. This test indicated that aside from the changing conditions and irregular banklines found in nature, rivers which erode their banks will meander, simply because a flow of water has a limited capacity for carrying sand along its bed. The only requirement for meandering is bank erosion.

It should be added that a stream may erode the banks only temporarily. In several tests, streams began eroding their banks, but the channel cross sections became so wide and shallow, and velocities were so reduced that bank erosion and meandering stopped. This resulting condition is found in nature in wide-shoaled sections of rivers.

J. F. FRIEDKIN

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the Transactions:

Vol. 26, no. 3, December 1945, p. 430, in Notes on Parícutin Volcano, second paragraph, seventh line; Kenneth E. Segerstrom of the United States Geological Survey, not D. J. Cederstrom, was in the party studying the Volcano in July.

Vol. 27, no. 1, February 1946, pp. 75 and 76 in the paper by Harold W. Hobbs; the figure on page 75 is Figure 7 with the title given on page 76; and similarly, the figure shown on page 76 is Figure 6 and should have the title given on page 75.

Vol. 27, no. 1, February 1946, p. 118 in the note on volcanic activity on Umnak Island in the Aleutians, the caldera is 1000 to 2000 feet deep, not 100 to 200 feet.

Education in the Earth Sciences--Howard A. Meyerhoff, writing in the A. A. A. S. Bulletin [Feb. 1946, pp. 10-11] calls attention to a brief article entitled "Earth Science in High Schools" by George A. Thiel published in School Science and Mathematics. The article points out the deplorable decline in the teaching of the science of the Earth in secondary schools during the last quarter-century and that a scant 1.2 per cent of the general science teachers in such schools of the Upper Mississippi Valley have had a course dealing with the physical features of the Earth. Dr. Meyerhoff points out that our neglect of the Earth as a subject of study extends to college students and teachers in every field of thought, including geology and geography. He comments that many political economists teach college courses in utter ignorance of the natural resources that have shaped the politics and international relations of nations, and that few historians are aware of the climatic and physiographic factors that have molded races and made history. Most teachers, he says, whether at the secondary or university level, are content to remain in ignorance of the things that lie on the periphery of their fields, with the unfortunate result that they impart their ignorance to those they teach.

It would seem that fundamental knowledge concerning the celestial body which is Man's home should be part and parcel of the intellectual equipment of every educated person. Only through such knowledge can men in various callings understand the implications and the interrelationships of the problems on which they work.

Earthquakes in January and February 1946--On January 8, a shock of nondestructive intensity shook a large part of Imperial Valley and southern California. On January 12, a strong shock originating in the Gulf of Alaska was felt along the nearby coast.

One of the strongest earthquakes in many years shook the State of Washington on February 14 at 19:18 P. S. T. The epicentral area is not definitely defined but lies somewhere on the Olympic Peninsula southwest of Seattle. The maximum intensity in the cities of Seattle, Tacoma, and Olympia was about VI (M-M scale of 1931), particularly on filled or soft ground. Knickknacks were overturned, and in some cases dishes and articles were thrown from shelves. Reports of cracked plaster, broken windows, and shattered chimneys were rare. A poorly-braced 50,000 gallon water tank on top of a grain elevator fell to the roof of the structure; the walls of an old packing plant collapsed; and several other buildings in Seattle, including the Sears Roebuck mail order building, were damaged.

On January 25, heavy shocks in the St. Moritz area of Switzerland caused severe damage, some injuries, and disrupted communications. It was felt throughout Switzerland. Sion, in the canton of Valais, was the most strongly shaken town. A number of aftershocks were reported.

On February 14, 276 persons were reported killed by an earthquake near Constantine, Algeria. The epicenter was reported southwest of Constantine. Relief expeditions were hampered by landslides which blocked the mountain trails.

The following provisional epicenters were reported by the United States Coast and Geodetic Survey cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismological stations.

Date	Time G. C. T.	Location		
January 5	1 h 15.0 m	15.5°N.,	91.0°W.	Guatemala
5	19 57.3	16 S.,	167 E.	New Hebrides Islands region
12	20 25.7	59 N.,	147.5 W.	Alaskan Gulf
February 15	3 17.8	47.3 N.,	122.7 W.	Seattle, Washington region

Legislation on scientific research--During the summer and fall of 1945, a number of bills were introduced in Congress relating to Federal support and direction of scientific research. These are S. 1297 (the Kilgore-Pepper-Johnson Bill), S. 1285 (the Magnuson Bill), S. 1248 (the Fulbright Bill), S. 825 (the Byrd Bill), and H. R. 3440 (the May Bill). The pros and cons of the various bills, and a resumé of their status in October, 1945 appeared in Science, [v. 102, pp. 411-416, Oct. 26, 1945]. Since that time, hearings have continued and in December, Senator Kilgore introduced a new bill (S. 1720) embodying many of the changes that seemed desirable. This was subsequently revived, and reintroduced as S. 1850 (Kilgore-Magnuson Bill), conveniently referred to as the final Senate Bill. It has the sponsorship also of Senators Johnson, Pepper, Fulbright, Saltonstall, Thomas, and Ferguson, and has been accepted by many scientists. Another bill, S. 1777 was introduced by Senator Willis at about the same time. This legislation on science is of utmost importance to members of the American Geophysical Union. Copies of these bills may be received from your senator or representative or by addressing a request to the Senate or House Office Building. S. 1850 was published in full in Science, [v. 103, pp. 225-230, p. 240, Feb. 22, 1946], and a review of the present status of the situation appeared in Science a week later [v. 103, pp. 270-273]. Though the May Bill has passed the House, hearings are still in progress in the Senate. Constructive comment is invited in an effort to achieve the best legislation possible.

Pan American Institute of Geography and History--The Fourth General Assembly of the Pan American Institute of Geography and History, and the Third Consultation on Cartography will be held in Caracas, Venezuela, August 22 to September 1, 1946. The agenda are broad, covering various branches of geophysics, including geodesy, seismology, terrestrial magnetism, hydrology, weather and climate, and soil erosion. A preparatory meeting of the Executive Committee of the Institute and the chairmen of committees of the Commission on Cartography was held April 1 to 7, 1946 in Mexico City. Robert H. Randall of the Bureau of the Budget and C. L. Garner of the United States Coast and Geodetic Survey were among the United States representatives at the meeting in Mexico City.

Wartime study of beaches--During the War, the Beach Erosion Board carried on extensive studies relating to beach conditions in connection with projected landing and other military operations, under the supervision of John L. Kingman, Brigadier General, Corps of Engineers. These studies covered such items as the determination of depths over offshore bars, the effects of waves and storms on artificial harbors, and the characteristics of waves approaching a beach. The Board has received commendations on the value and correctness of its intelligence reports from Combat Army Headquarters. The War Department has awarded Martin A. Mason, Principal Engineer on the work, a citation for Exceptional Meritorious Civilian Service, and William C. Krumbein a citation for Meritorious Civilian Service. Among the other members of AGU working actively on the studies were Garbis H. Kaulegan, Jay V. Hall, Jr., Morgan D. Dubrow, and Mrs. Clara S. Edmunds.

New dating of eruptions of Sunset Crater, Arizona--Harold S. Colton, director of the Museum of Northern Arizona, recently announced that the eruption of Sunset Crater, the youngest cone in the San Francisco Mountain volcanic field, is now believed to have occurred between 1046 and 1071 A. D., rather than between 875 and 910 A. D. Additional investigations of prehistoric Indian dwellings buried under ash from the crater, and information from dated timbers, have led to the revision of the estimate of the date of eruption, originally calculated by J. C. McGregor in 1936.

Evidence of volcanic activity at Crater Lake lacking--Fred W. Cater, Jr. made a 3-week stay at the rim of Crater Lake in January, after a snow slide had broken the cable to a recording hydrophone borrowed from the Navy Department and installed in the edge of the lake. Cater found no evidence of any disturbance in the lake other than normal wave action, saw no evidence of fish poisoning by volcanic emanations, and was unable to secure eye-witness accounts of abnormal activity of the surface of the lake earlier in the winter, although some unusual clouds had been seen in the caldera.

International Astronomical Union--The Executive Committee of the International Astronomical Union convened in Copenhagen, Denmark, on March 7, 1946. Three delegates, Otto Struve, Joel Stebbins, and Harlow Shapley, attended from the United States.

Faraday Medal--Sir Edward Appleton has been awarded the Faraday Medal of the Institution of Electrical Engineers, for the conspicuous services rendered by him in the advancement of electrical science, particularly in the field of radio-wave propagation. This Medal is awarded not oftener than annually either for notable scientific or industrial achievement in electrical engineering, or for conspicuous service rendered to the advancement of electrical science, without restriction upon nationality, country of residence, or membership of the Institution.

Royal Netherlands Meteorological Institute--The Royal Netherlands Meteorological Institute, which was unable to receive publications from abroad during the War, is now anxious to renew exchange relations with geophysical institutes and societies, and to receive geophysical publications which have been issued during the past five years. The Institute will send its publications issued during the War period and subsequently on an exchange basis. The address is: The Royal Netherlands Meteorological Institute, De Bilt, Holland.

Canadian Committee on Geophysics--A Committee on Geophysics has recently been formed as an associate committee of the National Research Council of Canada. Membership includes geophysicists from Federal and Provincial departments and the universities. Six sub-committees have been formed, one of which is on "Electric and Magnetic Phenomena of the Earth." Close cooperation is planned with the Meteorological Service, Dominion Observatory, Canadian Radio Wave Propagation Committee and the Arctic Institute of North America. Widespread interest is manifest not only in geophysical prospecting but also in long-term geophysical studies.

PERSONALIA

Pedro I. Aguerrevere, geophysicist and geologist and Financial Counselor to the Venezuelan Embassy in Washington was a delegate for the Government of Venezuela at the International Monetary Conference held in Savannah, Georgia in March 1946.

V. T. Allen has been appointed Head of the Department of Geology at St. Louis University, where he taught before joining the United States Geological Survey in 1942.

Gregory Breit and Merle A. Tuve were awarded fellowships in the Institute of Radio Engineers at the Winter Technical Meeting in 1946 "for pioneering in the experimental probing of the ionosphere and giving to the world the first publication of the experimental proof of the existence of the ionosphere; and for having initiated at an early date the pulse method of probing by reflection which is the basis of modern radar." Dr. Breit has returned to his duties in the Department of Physics at the University of Wisconsin; and Dr. Tuve has resumed his work at the Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Albert L. Cochran, recently returned from Europe where he served as Major in the Corps of Engineers, has been appointed Chief of the Reservoir Regulation and Hydrology Branch, Office of Chief of Engineers, United States Army.

N. W. Cummings has resigned his position with San Bernadino Valley Junior College to devote full time to scientific and research matters and personal business affairs.

John W. Dixon, until recently Assistant to the Commissioner of the Bureau of Reclamation has been designated Director of the Branch of Project Planning.

David E. Donley has accepted an appointment as hydraulic engineer with the Norfolk District of the U. S. Corps of Engineers in charge of the Hydrologic Unit. Until recently, he was on active service in the Ordnance Department of the Army as Lieutenant Colonel.

Richard A. Geyer, formerly associated with the Woods Hole Oceanographic Institution, is now with the Geophysics Research Division, Humble Oil and Refining Company, Houston, Texas.

Richard P. Goldthwait, formerly of Brown University and, during the war, in charge of special equipment investigations for the Army Air Corps at Wright Field, has been appointed Associate Professor of Geology at the Ohio State University.

Ross Gunn, Superintendent of the Mechanics and Electricity Division and the Aircraft Electrical Research Division of the Naval Research Laboratory, Washington, D. C. has been awarded the Navy's highest civilian honor, a citation for "Distinguished Civilian Service."

Gail A. Hathaway has been designated as Special Assistant to the Chief of Engineers, U. S. Army. He was formerly Head Engineer in the Engineering Division and Chief of Reservoir Regulation and Hydrology Branch, Office of Chief of Engineers, U. S. Army.

Harry H. Hess has returned from service as Lieutenant Commander with the Navy in the Pacific and is on duty at the Hydrographic Office of the Navy Department in Washington, D. C. He expects to return to inactive status in the Navy soon, and resume his duties at Princeton University.

Arthur T. Ippen, until recently Assistant Professor of Civil Engineering at Lehigh University, has accepted an appointment in the Department of Civil and Sanitary Engineering at Massachusetts Institute of Technology.

Richard H. Jahns, recently with the U. S. Geological Survey, has accepted an appointment as Assistant Professor in the Division of Geological Sciences, California Institute of Technology.

Robert S. Jones, is now engaged in investigations for the Division of Groundwater, U. S. Geological Survey, with headquarters in Tucson, Arizona. Until recently, he was a Lieutenant Commander in the Navy.

A. A. Kalinske, recently Associate Professor of Hydraulics, and Associate Director of the Iowa Institute of Hydraulic Research at the University of Iowa, and more recently, a member of the engineering staff of the Cleaver-Brooks Company of Milwaukee, has been appointed Associate Professor of Hydraulics at the University of Minnesota.

Robert A. Laurence, formerly Regional Geologist of the U. S. Geological Survey, with headquarters in Jefferson City, Tennessee, and Earl M. Irving, formerly with the Foreign Economic Administration in Central America, left Washington March 2 for Manila, P. I. Laurence is to be in charge of a cooperative program of the Foreign Geology Section of the Geological Survey and the Department of State to aid in the reconstruction of the Philippine mineral industries.

Oscar E. Meinzer, chief of the Ground-Water Division of the Water Resources Branch, U. S. Geological Survey was recently given an honorary degree as Doctor of Science at the Centennial celebration of Beloit College.

Wilber A. Nelson, who has been stationed in Washington, D. C. on war duty, has returned to his position at the University of Virginia as Head of the Department of Geology.

Arthur Richards will become a member of the staff of the Department of Geology at Southern Methodist University beginning March 1, 1946. Formerly he was with a party of the U. S. Geological Survey in the iron range of Michigan.

Richard A. Rowland, until recently stationed at the Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland has been discharged from the Army and has accepted a position as Section Leader in rock chemistry with the Shell Oil Company with headquarters in Houston, Texas.

Svein Rosseland, recently with the Division of War Resources at Columbia University has taken up duties in the Department of Astronomy at Princeton University.

M. Seppänen has been appointed Observer-in-Charge of the Sodankylä Observatory in Finland.

S. S. Steinberg, Dean of the College of Engineering, University of Maryland has been appointed Chairman of the Maryland Committee on Water Pollution, the new name for the State Pollution Committee. He succeeds John W. Sherwood.

E. Sucksdorff, head of the Sodankylä Observatory in Finland since 1927, was appointed Geophysicist of the Meteorological Office at Helsinki June 1, 1945. On January 1, 1946, he was chosen by the Finnish Academy of Sciences as Secretary of the Sodankyla Observatory, succeeding Professor Keränen, who had held that position for 27 years.

George C. Taylor has returned to the U. S. Geological Survey from the Navy, and has gone to Chile to study ground-water problems of the Atacama desert. He is taking the place of S. Spencer Nye, who recently returned from Chile because of illness.

Harry Bateman, Professor of Mathematics at California Institute of Technology died of a heart attack on a train in Utah on January 21, 1946, at the age of 63. At the time of his death, Professor Bateman was en route to New York to receive a medal from the Institute of Aeronautical Science for his outstanding work in aeronautics. He was born in Manchester, England, received his formal education at Cambridge, Göttingen, and Paris, and the degree of Doctor of Philosophy from Johns Hopkins University, and had been at California Institute of Technology since 1917.

Glenn L. Parker, Chief Hydraulic Engineer of the U. S. Geological Survey died on February 12, 1946 at the age of 61, following a very brief illness. Mr. Parker was born in Butte, Montana in 1884 and received a Bachelor of Science degree from the University of Kansas in 1906. He was deck officer in the United States Coast and Geodetic Survey in 1908 and served as hydraulic engineer in the U. S. Geological Survey since 1909. From 1913 to 1939 he was District Engineer of the Geological Survey at Tacoma, Washington and from 1939 until his death was Chief Hydraulic Engineer in charge of the nation-wide water investigational activities of the Survey.

Andrew R. Whitson, Professor of Soils at the University of Wisconsin, died suddenly on November 20, 1946 at the age of 75. He was born at Stanton, Minnesota, and received his formal education at the University of Wisconsin and Chicago University, taking some advanced work in Berlin later. He became a member of the staff of the University of Wisconsin in 1900, returning in 1941 after a fruitful career on the study of soils and the climatic factors in agriculture.

UNION, SECTION, AND COMMITTEE ACTIVITIES

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Minutes of January 25, 1946

The meeting was called to order at 14^h, January 25, 1946, by President Adams in the Tayloe Room of the Cosmos Club, Washington. D. C.

Present--Thirty persons were present, namely: L. H. Adams; K. H. Beij; W. H. Bucher; Ernst Cloos; L. P. Disney; J. A. Duerksen; J. A. Fleming; R. E. Fuller; N. C. Grover; H. D. Harradon; Earl Ingerson; David G. Knapp; W. D. Lambert; W. C. Lowdermilk; J. P. Marble; H. E. McComb; A. G. McNish; G. W. Musgrave; F. W. Reichelderfer; Irwin Roman; W. W. Rubey; Waldo L. Schmitt; Waldo E. Smith; V. C. Stechschulte; H. T. Stetson; W. B. Sutcliffe; C. H. Swick; W. T. Thom, Jr.; R. H. Weightman; and C. A. Whitten. Excused because of absence from the city or for other reasons were: E. A. Eckhardt; R. M. Field; M. K. Hubbert; and H. U. Sverdrup.

Approval of Minutes--The minutes of the General Assembly of the Union were published in the Transactions as were those of the Executive Committee of June 1, 1945, as approved in abstract at the meeting on June 16, 1945, and of June 16, 1945 [v. 26, pp. 139-143, 161-164, and 170-171, 1945].

General Secretary's Report

Executive Committee--Because of revisions in Statutes and By-Laws effective July 31, 1945, the following have been added as members of the Executive Committee: W. C. Lowdermilk, past President of the Union; past Presidents of Sections--L. H. Adams [already a member], (Tectonophysics), A. F. Buddington (Volcanology), A. E. Eckhardt (Terrestrial Magnetism and Electricity), N. C. Grover (Hydrology), H. E. McComb (Seismology), C. W. Thornthwaite (Meteorology), P. C. Whitney (Oceanography), R. M. Wilson (Geodesy); Secretaries of Sections--K. H. Beij (Hydrology), L. P. Disney (Oceanography), J. A. Duerksen (Geodesy), H. D. Harradon [already a member], (Meteorology), M. K. Hubbert (Tectonophysics), David G. Knapp (Terrestrial Magnetism and Electricity), Leonard M. Murphy (Seismology), F. G. Wells (Volcanology); Committees--H. F. Johnston, because of protracted illness, resigned as Chairman of the Standing Committee on Membership and G. W. Musgrave was appointed in his place November 26, 1945, and R. H. Weightman, Chairman of the Standing Committee on Nominations; Executive Secretary of the Union, Waldo E. Smith. The late W. B. Cannon's successor as Chairman of the Division of Foreign Relations of the National Research Council, Detlev W. Bronk, is now ex-officio member of the Executive Committee. N. H. Heck, because of ill health resigned as President of the International Association of Seismology and is thus, after many long years of service, no longer a member of the Executive Committee.

The Standing Committee on Nominations was appointed with R. Hanson Weightman as Chairman and J. B. Macelwane, C. A. Heiland, Frank J. Veihmeyer, and William W. Rubey as members.

Irwin Roman was added to the Committee on Membership to represent the Section of Terrestrial Magnetism and Electricity in place of H. F. Johnston, who asked to be relieved because of illness.

Frank Neumann, co-editor for the Section of Seismology, because of heavy burden of his official work, resigned from the Editorial and Publications Committee.

Frank S. Borden was appointed Chairman of the Committee on Surveys and Maps to replace C. H. Swick upon the latter's retirement from the United States Coast and Geodetic Survey.

George P. Woollard advised by letter concerning the status of the gravity-meter loaned to the Union by the Humble Oil and Refining Company. His letter was referred to the Special Committee on Geophysical and Geological Study of Continents.

C. H. Swick resigned as Chairman of the Committee on Budget and R. M. Wilson was appointed as Chairman. Swick thus ceases to be a member of the Executive Committee; the General Secretary's recommendation that in the case of such resignations, the persons be invited to attend the two succeeding Executive Committee meetings in order to aid in the preservation of continuity was approved.

Financial report--The General Secretary reported cash balance of Union was $6,743.79 as of January 1, 1946--$6,584.69 in current fund and $159.10 in William Bowie Medal Fund; bills receivable including arrears in dues totaled about $1200 and bills payable about $1100.

Item of $0.50 against Dekkir en Nordenmann's account--outstanding since September 26, 1940--was approved to be eliminated.

Authority was given for transfers from unexpended balances in items of Budget for 1946 as follows: $400 to item Stationery and Miscellaneous; $200 to item Committees.

Payments from Rockefeller Foundation grant of $3500 for July to December, 1945, and of $1750 for January to March, 1946, were noted. No payment has been received as yet on account of the Robert E. Horton bequest of $5000 but the large number of notes and pamphlets (some 3500 pounds) bequeathed to the Union was received January 24, 1946.

Membership--During June 1, 1945, to January 18, 1946, 259 new members were elected. The following tables summarize present membership.

Membership as of June 1, 1945	2445	
New members	259	
Inactive to active	5	
		2709
Deaths reported	8	
Active to inactive	8	
Resigned	7	
		23
Total January 18, 1946		2686

These are classified as follows:

Life members (because of retirement)	7	
Life members (paid)	3	
Corresponding members	4	
Members and Associates	2672	
Total January 18, 1946		2686

The eight deaths reported were as follows: Lieutenant Bruno Ulak (killed in action, date unknown); Milton H. Schoerpner (killed in France, September 12, 1944); Rudolph G. Kasel (died June 14, 1945); Frederic E. Clements (died July 26, 1945); Robert H. Goddard (died August 10, 1945); Homer D. Erwin (died September 10, 1945); Robert W. Adams (died October 13, 1945); and Gilbert C. Dobson (died December 29, 1945).

Delinquencies in dues were reported as follows: (a) Six members in arrears for 1942-1945; (b) 12 for 1943-45; (c) 49 for 1944 and 1945; and 81 for 1945. As regards groups (a) and (b) it was agreed that the individuals concerned should be dropped from the rolls if one final effort failed of response with the provision that those who are found to have been in war service or unable to remit dues because of the war may be reinstated upon their request. As regards group (c) it was agreed that there should be one further attempt to get payment of dues and if dues are not paid by May 1, 1946, the General Secretary was instructed to drop any who have not so been placed in good standing, subject, however, to the provision above stated for groups (a) and (b). It was approved that members in enemy-occupied lands may remit dues in full and receive all back publications not previously sent, or consider such period as each desires as on inactive status; those not heard from may be placed on inactive status pending further word.

It was noted that, under strict interpretation of the Statutes and By-Laws, citizens of countries other than the United States are not eligible for election as Associate Members. As regards eligibility of nationals of ex-enemy countries to election as Members it was decided that each case must be considered on its merits.

The method of handling of funds received for life memberships was referred for consideration and recommendation by the Committee on Budget.

National Research Council--Ernst Cloos has been appointed to the Division of Geology and Geography to represent the AGU for a three-year term beginning July 1, 1946; he succeeds Jno. A. Fleming.

Publications--In July, 1945, 3000 copies of each of the last two Parts V and VI of the Transactions of 1944 were received from the printer and distributed. Nos. 1, 2, and 3, to complete volume

26 of the Transactions (1945) were published in an edition of 3500 copies each and distributed. Copy for No. 1 (February) of volume 27 went to press January 25, 1946.

It was carried that not in excess of 100 copies each of Nos. 1, 2, and 3 of volume 26 of the Transactions may be sent, with appropriate letters, to technical libraries inviting subscriptions.

International Union of Geodesy and Geophysics--Fleming, Lambert, and Field of the Union attended meetings of the Executive Committees of the International Council of Scientific Unions in London, England, (December 4 and 5, 1945) and of the International Union of Geodesy and Geophysics in Oxford, England (December 11-14, 1945) and reports of activities are published in the Transactions [v. 27, pp. 145-148 and pp. 209-214].

Meetings--Resolutions adopted at the Twenty-Sixth Annual Meeting of the Union have been transmitted through the National Research Council.

Approval was given for the Regional Meeting of the South Pacific Area of the Section of Hydrology in cooperation with other organizations at Sacramento, California, February 27 and 28, 1946. The Regional Meeting of the North Pacific Area at some place in the Pacific Northwest, planned for June, 1946, was also approved. [This plan was later postponed, because of local circumstances as regards lack of hotel reservations.]

Steps have been taken for organization of a Washington Group of the Section of Hydrology. One informal luncheon was held in November, 1945 [see Trans., v. 27, pp. 149-150] and a second is scheduled for February 18, 1946 [v. 27, p. 305]. Plans for formal organization of the group will be presented later.

National Roster--Director George A. Works of the National Roster has reported that 2,800,000 copies of a leaflet "The Job of the Geophysicist" are being distributed through the separation centers of the Armed Forces and otherwise; this leaflet is a revised and condensed version of draft prepared by the Executive Secretary. The leaflet mentions the Union as a source of information as regards education and other matters relating to Geophysicists and many inquiries are being received. A second publication "Vocational Monograph on the Profession of Geophysics" is in preparation by the National Roster and is based on a draft prepared in the office of the Union, which incorporated the suggestions of members of the Executive Committee and others. A proposed third publication, "Handbook of Descriptions of Specialized Fields in Geophysics," will probably be abandoned because of enlargement of the "Vocational Monograph."

American Standard Association--G. C. Mattison, representing the Union in this Association [see Trans., v. 26, p. 476 and v. 27, p. 149] requests suggestions from Members interested in photography in the various standards that are being suggested from time to time.

Miscellaneous--H. E. Culver represented the Union at the inauguration of Wilson M. Compton as President of Washington State College on December 11, 1945.

Action on General Secretary's Report--Matters reported by the General Secretary and which had not been specifically acted upon as above indicated, were accepted and approved.

Reports of Standing Committees

Membership--Chairman Musgrave reported briefly on activities since his appointment in November 1945. An intensive drive through letters to all Members and Associates to solicit properly qualified persons for election to the Union was initiated.

Meetings--Chairman Marble recommended the Twenty-Seventh Annual Meeting be set for May 27-29, 1946, at George Washington University. It was moved and carried that this recommendation be accepted. Chairman Marble's suggestion that one or more evening meetings or symposia be held during the year--one, if possible, at the time of the meeting of the Executive Committee during the fall or winter--was favorably received.

Nominations--Chairman Weightman's preliminary report on procedure for nominations and elections was discussed and it was agreed that the report be circulated to all members of the Executive Committee for detailed comments or suggestions, and that such written comments and suggestions, when received, be forwarded for consideration and further report by the Committee to the Executive Committee at the time of the Twenty-Seventh Annual Meeting, following which a

tentative report is to be published in the Transactions for discussion by the Union's membership. It was agreed that the final procedures should be completed by October, 1946.

Audit--The published report of Committee on Audit for fiscal year ending June 30, 1945, was approved [see Trans., v. 26, pp. 166-168].

Reports of Special Committees

Geophysical and Geological Study of Continents--Chairman Thom gave a brief report, calling attention to the need to collaborate closely with Canadian colleagues.

Cosmic-Terrestrial Relationships--Chairman Stetson reported briefly on a conference held in Needham, Massachusetts, on December 11, 1945, pertaining to solar activity and radio communication.

Surveys and Maps--Chairman Borden was not present, but Retiring Chairman Swick presented a brief report, covering especially the response received from Secretary Forrestal concerning the Resolution on an Interdepartmental Map Board [see Trans., v. 26, p. 142].

Affiliation with American Geophysical Institute--Chairman Thom reported briefly with regard to the Informal Coordinating Assembly of representatives of 13 geoscientific societies held at the National Academy of Sciences-National Research Council Building in Washington, D. C., October 12-13, 1945, at which he was the AGU representative. The transcript of the detailed discussion has been circulated to those present and to the organizations that they represented. The following were the tentative conclusions reached by the group as reported by Dr. Thom.

(1) That the delegates agreed that some sort of council, institute, or federation of the Earth-Science societies should be formed in order to provide an agency for the determination of the collective opinion in Earth Science within the realm of the field of each group.

(2) That a Committee of Delegates, consisting of C. L. Camp (Chairman), I. H. Cram, Carey Croneis, P. F. Kerr, and C. R. Longwell, should prepare a specific statement of the purposes such an organization would be expected to serve.

(3) That another Committee, consisting of W. B. Heroy (Chairman), I. H. Cram, Carey Croneis, C. R. Longwell, and W. T. Thom, Jr., should prepare a supplementary statement regarding organization procedures recommended for the accomplishment of these purposes.

(4) That as, and when, reports of these committees have matured, they should be reported back by each delegate to the society or group that he represents, for consideration by that group.

(5) That the meeting of the Informal Coordinating Assembly of October 12-13, 1945, should reconvene after the thirteen interested societies have decided what instructions to give their respective delegates concerning the projected formation of an Americal Geological Council or Institute.

No action is required at this time.

It was moved and carried that all above-listed reports be received.

New Business

It was carried that the item for Travel in the current year's Budget should be used to the extent necessary to defray transportation expenses incurred incident to special travel to attend this meeting of the Executive Committee.

There being no further business, adjournment was taken at 16^{h}45^m.

JNO. A. FLEMING
General Secretary
WALDO E. SMITH
Executive Secretary

Transactions, American Geophysical Union Volume 27, Number II April 1946

UNION, SECTION, AND COMMITTEE ACTIVITIES

SECTION ACTIVITIES

Section of Terrestrial Magnetism and Electricity

ADDENDUM: Minutes of the Annual Meeting of 1945, Section of Terrestrial Magnetism and Electricity, American Geophysical Union

Summary of oral discussion of technical papers--The first paper discussed was the one presented by Wells [see v. 26, pp. 381-387, Dec. 1945]. C. W. Gartlein asked the author to elaborate on the indication of intensities in terms of frequency. Irwin Roman referred to the experiments of Nipher [Variations in the Earth's magnetic field, Trans. Acad. Sci., St. Louis, v. 22, pp. 109-124, 1913, and v. 23, pp. 153-162, 1916] on the effects of sunlight, passing clouds, and sound waves on a suspended intensity-magnet. S. E. Forbush brought out the possibility that seasonal effects would mask any 27-day recurrence effect. H. H. Howe suggested that each day might be compared with the monthly mean, to reduce the seasonal effects. Wells explained that the intensity was indicated by the highest frequency at which reflections were obtained. The President (H. F. Johnston) remarked that he understood work was being continued on the research, and that some interesting results already obtained could not yet be disclosed because of security restrictions.

The discussion that took place after the presentation of the paper by Nelson and Campbell [v. 26, pp. 379-380] indicated considerable interest in the phenomena of spontaneous changes in magnets. H. G. Dorsey mentioned his experience with antimony, particularly with regard to its changes of dimensions. The possibility of holding the temperature of the magnet constant was suggested by E. B. Roberts. H. E. McComb stressed the protracted scope of the observations needed to bring out such minute effects, and referred to the possibility of a change in the pole-distance, and the well-known instability of many alloys in other respects. In response to the various comments, Howe pointed out that if the increase were halted now by keeping the magnet at constant temperature, there would be no evidence that it would not have stopped anyway. He also noted that there was no indication in the data thus far accumulated of any change in the distribution coefficients, though such a change would necessarily accompany any change in the pole-distance.

The discussion following the paper by Rooney [abstract, v. 27, p. 59] was led by O. H. Gish, who complimented the speaker on the clarity with which the data were assembled, and noted that unexplained January anomalies appear in many localities, for instance a less pronounced but seemingly locally restricted enhancement of certain features in the Cheltenham magnetic traces in that month. He referred to difficulties encountered by Sydney Chapman in coordinating magnetic daily variations at different observatories situated along a parallel of latitude (recalling particularly the anomalous pattern found at one of the Russian stations) and to the obstacles to be met in the acceptance of overwhelming indications of local effects. The conductivity of the ocean mantle has been considered, but any satisfactory explanation of the phenomenon along these lines in conjunction with related magnetic effects seems to call for a more deep-seated action, albeit it is difficult to understand how the latter could respond to seasonal conditions. He then remarked that the phenomenon reported in the paper is a departure from what one would expect as the norm, and deserves a great deal of attention.

A. G. McNish raised the question whether the observed effects might not be a resultant of the peculiarities of lunar-daily variation operating in conjunction with solar-daily variation, when the two kinds of variation are in the proper phase relation. He referred to studies of magnetic traces which had indicated such effects at Huancayo and Watheroo, with seasonal complications such as the overhead passage of the center of the current system in certain months at Watheroo, and its tendency at those times to shift back and forth from day to day. Rooney thought that the persistence of the phenomenon, as evidenced in the twelve-year span of the records studied, was unfavorable to a lunar explanation, and Gish suggested that the lunar effects would be expected to present a zonal pattern, rather than a local peculiarity such as seemed to be brought out in the present study. McNish believed that this was not necessarily a conclusive argument, declaring that there might be a cumulative effect in a particular area, such as the remarkable enhancement of the ratio of lunar- to solar-daily variation at Huancayo, this ratio being larger there than at any other station. He asked whether there had been a definite study of the lunar variation in the present instance. Wells remarked on the anomalous winter behaviour of the F_2 region of the ionosphere, in presenting greater intensities than in summer. David G. Knapp asked whether this suggestion implied extension of d-c. conductivity to the upper reaches of the ionosphere, and Wells replied that it did not, but that the F_2 region seems to react most strikingly to all forms of magnetic disturbance.

Howe noted an anomaly that had been found in the magnetic daily variation at Honolulu, namely that the September curve for horizontal intensity is consistently different from the mean of the August and October curves. E. H. Vestine inquired whether certain data indicating an anomaly in April at an observatory in Spain had been examined in connection with the present investigation.

Rooney referred to the ionosphere effects as being of the kind that would be expected to affect many stations in a systematic way, whereas the present effect calls for a definite spatial discrimination, as the effect is entirely absent at some other stations. He also reported that the phenomenon in question seemed to have no relation to solar activity, and pointed out that the effects of overhead passage of the center of the current system ought to be more pronounced in summer rather than in winter. He stated that the lunar variation had been studied but that it only amounted to between 16 and 20 per cent as much as the solar component. He indicated that while the Spanish data had not been examined in detail, the anomaly referred to was much less pronounced than the present one.

Gish pointed out in connection with the paper by Hess and Balling [v. 26, pp. 237-240] that the topic was of interest in relation to cosmic-ray work, as it concerned the correction for secondary radiation necessary in such measurements. There seemed to be effects too large to be accounted for by ordinary transition effects. He remarked that the apparent linearity of the relation between rate of ionization per cc and area of the body would suggest a wall effect rather than a transition effect, since the latter ought to yield a curve that would be convex upward.

After the presentation of the paper by Kovach [v. 26, pp. 241-248] G. R. Wait referred to some of his findings with regard to ionization of the air. No relation with barometric pressure was found, but there was good inverse correlation between the ionization of the air and the author's reported radon content of soil gas. Gish commented on the complexity of the phenomena, and referred to the possibility of investigating any time-lag in the response of the instrument to soil conditions by analyzing data covering pressure-changes with different periodicities.

DAVID G. KNAPP, Secretary

Section of Hydrology

Regional Meeting at Sacramento--The regional meeting of the Section of Hydrology called by the South Pacific Regional Committee was held on February 26, 27, and 28 in cooperation with the American Society of Agricultural Engineers and the Western Snow Conference. February 27 was the day especially allotted to the American Geophysical Union. F. J. Veihmeyer, Chairman of the Regional Committee, reports splendid attendance (104 registered on February 27) and great and sustained interest, with many lively discussions. Thirty papers were presented during the three-day session, nine on February 27.

Later issued of the Transactions will cover additional information concerning this meeting, including papers presented.

Regional Meeting in Pacific Northwest postponed--Word has come from J. C. Stevens, Chairman of the North Pacific Regional Committee of the Section of Hydrology that local conditions require the postponement of the meeting tentatively set for June 1946, until sometime in 1947.

Second Meeting of the Washington Group--Eighty members and guests gathered at Barker Hall of the Y. W. C. A., Washington, D. C. on February 18, 1946.

First order of business was the election of officers, with the following results: Chairman, D. B. Krimgold; Vice-Chairman, Carl F. Izzard; Secretary, Bernard Frank. Krimgold indicated the desirability of developing a set of By-Laws for the Group, and of other necessary arrangements for systematizing relationships with the parent Section of Hydrology and the AGU as a whole. The Chairman then introduced the speaker, Merrill Bernard, paying tribute to his many accomplishments.

The speaker gave an absorbing account of his visits to the Soviet Union and his inspection of their hydrologic activities. Although operating under many difficulties and often handicapped by lack of the best equipment, technical standards are generally high, and record-keeping and analyses of climatic and streamflow data are detailed and efficient. Women are employed to a considerable extent on the meteorological and flood forecasting work, sharing equally with the men the hardships and responsibilities of life at the various field stations.

The meeting adjourned at $14^{h}00^{m}$

BERNARD FRANK, Secretary

SPECIAL ANNOUNCEMENTS

Twenty-Seventh Annual Meeting--The Twenty-Seventh Annual Meeting of the Union will be held in the Hall of Government, George Washington University, Washington, D. C., May 27 to 29, 1946, as noted on a front fly-leaf of the February issue of the Transactions. Inadvertently, notice concerning the meeting of the Section of Oceanography was omitted. Persons interested in that Section should communicate with the Secretary of the Section, L. P. Disney, U. S. Coast and Geodetic Survey, Washington 25, D. C. A second notice of the Section's meeting was mailed to each Member early in April. Plans are progressing, and indicate an interesting and successful session.

Changes of Address--Many changes of address have been received in the last few months, but the return of Transactions and other communications indicates that AGU has not been entirely successful in maintaining an up-to-date file of addresses of the membership. If you have recently changed your address, or anticipate a change, please advise the Executive Secretary promptly. Experience has proven that the use of two addresses for a member, or an attempt to withold certain classes of mail, forwarding others, is confusing and costly.

Back issues of Transactions needed--The American Geophysical Union has frequent calls for back issues of the Transactions and will be grateful for the return of any issues for which Members have no further need. Transactions of 1944 and earlier years should be sent Book Post (four cents for the first pound and three cents for each additional pound); those later than 1944 should be sent at magazine rates (one cent for each two ounces). The Union will be glad to refund postage.

Change in arrangement of the contents of the Transactions--In the four previous bimonthly numbers of the Transactions, reviews, abstracts, bibliography, notes, and personalia have been handled as "filler" material, to avoid partially filled pages and to permit all papers to begin on an odd-numbered page. In response to criticism of the resulting dispersion through each issue, the Editors in the current issue, have assembled all of this material together. The equivalent of about five pages consequently remains unused in the partial pages at the ends of papers, and papers start on the next succeeding full page. In the table of contents of the current issue, the pagination runs consecutively from the lowest to the highest number, avoiding the back-tracking that the previous arrangement involved. Comments relative to this and other matters regarding format of the Transactions are invited.

Change in presentation of reference material--In previous issues of the Transactions, reference material was numbered, and reference in the text was by numbers. Beginning with the current issue, the Editors have decided that authors be listed alphabetically with the surname first and that references are to be by author's name and year. When references to one author include more than one for the same year, a distinction is made by placing a letter--a, b, etc.--after the year.

Authors of papers submitted for publication are requested, when convenient, to follow this new convention, which has some advantages over the system first included in the Union's suggestions for preparation of manuscripts for its Transactions.

Special Announcements--With the issuance of the Transactions as a bimonthly, the need for mailing separate letters to the membership regarding meetings, elections, and other general matters will be much less. For announcements relating to such matters, members are urged henceforth to refer to the last page of each issue of the Transactions.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 27 JUNE 1946 Number III

ADJUSTMENT OF TRAVERSE

Earl Saunders Belote

Abstract--This paper outlines a method of relating the corrections to the measured distances and the corrections to the observed angles in the adjustment of traverse to achieve a fit with the fixed data with the least distortion. The method is flexible enough to meet the needs of various types of problems; although it does not give absolute results, it should prove very satisfactory if used with judgment.

Theoretical development--The determination of the changes in the measured lengths in order to achieve the best fit with the fixed data has been the chief problem of the adjustment of traverse. The United States Coast and Geodetic Survey has recently used a method of relating these corrections and the corrections to observed angles, which has produced very satisfactory results. The following material presents a short discussion of the theory and then shows its application to specific problems, both on the spheroid and on the state plane coordinate systems. Due to the limitations of space most of the computations which have been done according to previously published procedures have been omitted from the material shown in the specific problems, and no sketches of the traverse lines are shown.

The equations to hold the fixed position of the terminal point are found from preliminary computations as discussed on pages 69 to 81 of the Manual of Triangulation Computation and Adjustment, U. S. Coast and Geodetic Survey Special Publication No. 138. In traverse, this computation is very much simplified, since only the azimuth angles enter. The equations resulting from this computation have only the unknown corrections to the angles.

Upon the hypothesis that all the lengths in the traverse or all the lengths in specified sections of the traverse shall be changed by a constant ratio, the effect of this change may be expressed as a part of the constant term of each equation. If this unknown ratio is expressed as the change in the sixth place of the logarithm, the effect on the constant of the latitude equation is this logarithmic change multiplied by the total difference of latitude expressed in minutes of arc for the section of traverse considered, and the effect of the longitude equation is the change multiplied by the difference in longitude.

Where all the lengths of the entire traverse are changed by the same ratio, the constant term of the latitude equation will be in the form $N_1 + a_1k$, and the constant term of the longitude equation, in the form $N_2 + a_2k$, where N_1 is equal to original constant term of the latitude equation, a_1 the total difference in latitude expressed in minutes, and k the variable change in the sixth place of the logarithm; and similar values for the constant term of the longitude equation.

These constants as expressed are carried through the forward solution without any preliminary attempt to evaluate k. Since the constant term is now expressed as a polynomial, at the end of the forward solution, the sum of the squares of the corrections to the angles is found in the form: $ak^2 + 2bk + c$. The value of k which will produce a minimum for this expression is equal to $-(b/a)$. If this value is reasonable, it is assigned to k and the resulting corrections to the angles obtained in the usual manner. The ratio corresponding to a given value of k is most easily found by dividing this value by the modulus of the common logarithm also expressed in units of the sixth place and depending upon the algebraic sign of k either adding or subtracting this quotient from unity.

In those cases in which it is desirable to correct various sections of a traverse line by different ratios, k_1, k_2, etc., coefficients of the k's are determined by the difference of latitude and longitude of the initial and terminal stations of the sections of the line to which they are to be applied. The resulting sum of the squares of the corrections to the angles found at the end of the forward solution is in the form:

$$a_1 k_1^2 + 2b_1 k_1 k_2 + 2c_1 k_1 k_3 + \ldots . 2m_1 k_1 + b_2 k_2^2 + 2c_2 k_2 k_3 + \ldots . 2m_2 k_2 + c_3 k_3^2 + \ldots . + 2m_3 k_3 + N$$

The minimum value is found by setting the partial derivatives equal to zero. This results in a small set of symmetrical equations which may be solved in the same manner as the regular forward solution, that is,

$$
\begin{aligned}
a_1 k_1 + b_1 k_2 + c_1 k_3 + \ldots + m_1 &= 0 \\
b_1 k_1 + b_2 k_2 + c_2 k_3 + \ldots + m_2 &= 0 \\
c_1 k_1 + c_2 k_2 + c_3 k_3 + \ldots + m_3 &= 0
\end{aligned}
$$

Traverse line, Verna to Goodrich--Apply this procedure in its simplest form to the traverse line from Verna to Goodrich, in which we have the fixed position for Verna 27°21′53″.943 of latitude and the 82°16′06″.347 of longitude, and the fixed position of Goodrich 27°20′18″.333 of latitude and the 82°22′42″.286 of longitude. The fixed azimuth Verna to Verna azimuth mark 178°20′ 28″.3 and Goodrich to Goodrich azimuth mark 86°07′59″.2.

Starting from the fixed position and azimuth at Verna and using the observed angles and measured lengths listed in Table 3 with the adjusted values and computing through we obtain the following three condition equations:

$$
\begin{aligned}
&\text{(Azimuth)-- } 0 = +32.1 + (1) + (2) + (3) + (4) + (5) + (6) + (7) + (8) + (9) + (10) \\
&\qquad + (11) + (12) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1) \\
&\text{(Latitude)-- } 0 = +35.4674 - \underline{1.59k} + 12.39\,(1) + 12.33\,(2) + 12.28\,(3) + 12.28\,(4) \\
&\qquad + 10.10\,(5) + 7.09\,(6) + 5.70\,(7) + 5.21\,(8) + 4.38\,(9) + 3.46\,(10) \\
&\qquad + 1.22\,(11) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2) \\
&\text{(Longitude)- } 0 = +24.6100 + \underline{6.59k} + 3.75\,(1) + 1.65\,(2) + 0.50\,(3) - 0.64\,(4) - 0.61\,(5) \\
&\qquad - 0.57\,(6) + 0.19\,(7) + 0.00\,(8) + 0.00\,(9) - 0.05\,(10) - 0.02\,(11) \ldots\ldots (3)
\end{aligned}
$$

The coefficient of k in the latitude equation is the computed latitude of Goodrich minus the fixed latitude of Verna or (27°20′.31 - 27°21′.90) expressed in minutes of arc. The coefficient of k in the longitude equation is the computed longitude of Goodrich minus the fixed longitude of Verna or (82°22′.70 - 82°16′.11). These three condition equations result in the solution shown in Table 1.

Table 1--Solution of three condition equations, Verna to Goodrich traverse line

1	2	3	k	η	Σ
+ 12.0000	+ 86.44	+ 4.20	.....	+ 32.1	+ 134.74
C_1	- 7.203333	- 0.350000		- 2.675000	- 11.228333
	+ 851.6944	+ 55.7711	- 1.59	+ 35.4674	+ 1027.7829
	+ 229.0383	+ 25.5171	- 1.5900	- 195.7596	+ 57.2058
	C_2	- 0.111410	+ 0.006942	+ 0.854702	- 0.249766
		+ 18.1806	+ 6.59	+ 24.6100	+ 109.3517
		+ 13.8677	+ 6.7671	+ 35.1845	+ 55.8193
		C_3	- 0.487976	- 2.537155	- 4.025131

All of the C's are shown in terms of the constant and the variable k.

In order to determine the sum of the squares of the corrections to the angles we must determine the sum of products in the k and η columns. Referring to these as "accumulations," we will define the accumulation of the product of k times k = (-1.59) × (+0.006942) + (+6.7671) × (-0.487976) = - 3.31322; the accumulation of k times η = (-1.59) × (+0.854702) + (+6.7671) × (-2.537155) = - 18.52816; and the accumulation of k times Σ = (-1.59) × (-0.249766) + (+6.7671) × (-4.025131) = - 26.84134; the accumulations of product of η times η, η times Σ, and Σ times Σ are computed in a like manner, giving the results shown in Table 2. These products may be checked by subtracting the sum of the original normal terms, adding each of the products in a line, and subtracting term in the Σ column. For example: The sum of the original normal in the (η column) is (+32.1 + 35.4674 + 24.6100) or + 92.1774; (-92.1774 - 18.52816 - 342.45215) = - 453.15771 or 0.00009 less than the item shown in the Σ column.

Table 2--Results of accumulation computations, Verna to Goodrich traverse line

	k	η	Σ	Check
Original normal terms	+ 5.00	+ 92.1774	+ 1271.7746	
k	- 3.31322	- 18.52816	- 26.84134	- 0.00004
η	. . . . .	+ 342.45215	- 453.15762	- 0.00009
Σ	. . . . .	. . . . .	- 1751.87365	+ 0.00009

From the checked accumulations the sum of the squares of the corrections to the angles is equal to $+ 3.31322k^2 + 2(18.52816)k + 342.45215$. This expression is a minimum when k is $= - 18.52816/3.31325 = - 5.59219$. The factor by which all the lengths should be multiplied is $1 - (5.59219/434294.48) = 0.9999871235$. Using - 5.59219 for k in the solution of the equation $C_1 = - 8.46529$; $C_2 = + 0.79452$; $C_3 = + 0.19170$. The corrections to the angles are computed from these three values and the final results are:

Table 3--Observed and adjusted traverse data, Verna to Goodrich

Station	Angle		Length	
	Observed	Adjusted	Measured	Adjusted
Azimuth mark	° ′ ″	° ′ ″	meters	meters
Verna	183 21 25.8	183 21 27.9	1,649.958	1,649.937
A - 11	181 58 17.2	181 58 18.8	900.081	900.069
T. P. 1	176 44 05.8	176 44 07.2	881.008	880.997
B - 11	270 13 46.7	270 13 47.9	1,899.856	1,899.832
C - 11	180 05 17.2	180 05 16.6	2,649.786	2,649.752
D - 11	205 24 23.5	205 24 20.6	1,357.372	1,357.355
T. P. 2	133 44 01.0	133 43 57.1	454.687	454.681
T. P. 3	200 20 58.8	200 20 54.5	725.030	725.021
T. P. 4	177 32 44.1	177 32 39.1	815.581	815.570
E - 11	182 30 29.9	182 30 24.2	1,950.198	1,950.173
F - 11	180 31 46.9	180 31 39.4	1,086.134	1,086.120
Goodrich	175 23 47.9	175 23 39.4		
Azimuth mark				

Note: This table lists the angles at the station from the station above clockwise to the station below. The lengths are from the station to the station below.

Traverse line, Point to John to Mesa--In a more complicated adjustment traverse on the spheroid we are holding three fixed positions and three fixed azimuths as shown in Table 4.

Table 4--Fixed positions and azimuths of traverse line, Point to John to Mesa

Station	Latitude	Longitude	Line		Azimuth
			From	To	
	° ′ ″	° ′ ″			° ′ ″
Point	30 34 56.474	88 28 57.104	Point	Big	5 55 03.4
John	30 40 48.052	88 30 22.876	Hub	Mont	182 04 31.7
Mesa	30 50 46.270	88 31 13.253	Mesa	Ward	132 37 46.0

As before, preliminary computations are started with the fixed position and azimuth at Point and carried throughout the traverse line and result in the following six condition equations:

(Azimuth)-- $0 = + 5.1 + (1) + (2) + (3) + (4) + (5) + (6) + (7) + (8) + (9) + (10)$
$+ (11) + (12)$ . . . . (1)

Table 5--Solution of six condition equations, Point to John to Mesa traverse line

1	2	3	4	5	6	k_1	k_2	η	Σ
+ 12.0000	....	+ 12.07	- 19.79	+ 29.67	- 58.12	....	....	+ 5.1	- 19.07
C_1	....	- 1.005833	+ 1.649167	- 2.472500	+ 4.843333	....	....	- 0.425000	+ 1.589167
	+ 6.0000	....	....	+ 4.42	- 6.65	....	....	+ 1.3	+ 5.07
	C_2	....	....	- 0.736667	+ 1.108333	....	....	- 0.216667	- 0.845001
		+ 31.3845	- 53.3108	+ 49.5288	- 80.1566	+ 5.86	....	- 47.7724	- 82.3965
		+ 19.2441	- 33.4054	+ 19.6857	- 21.6976	+ 5.8600	....	- 52.9022	- 63.2154
		C_3	+ 1.735877	- 1.022947	+ 1.127494	- 0.304509	....	+ 2.749009	+ 3.284924
			+ 102.0841	- 83.0804	+ 137.3389	+ 0.715	....	+ 17.3718	+ 101.3286
			+ 11.4594	+ 0.0223	+ 3.8250	+ 10.8872	....	- 66.0492	- 39.8553
			C_4	- 0.001946	- 0.333787	- 0.950067	....	+ 5.763757	+ 3.477957
				+ 99.6353	- 172.8941	+ 5.86	+ 9.97	- 115.8118	- 172.7022
				+ 2.8827	- 2.1055	- 0.1557	+ 9.9700	- 75.1345	- 64.5430
				C_5	+ 0.730392	+ 0.054012	- 3.458463	+ 26.063933	+ 22.389774
					+ 322.0009	+ 0.286	+ 0.168	+ 6.5144	+ 148.4875
					+ 5.8575	+ 3.1454	+ 7.4500	- 59.8219	- 43.3690
					C_6	- 0.536987	- 1.271874	+ 10.212872	+ 7.404011

(Azimuth) -- 0 = + 1.3 + (13) + (14) + (15) + (16) + (17) + (18). (2)

(Latitude) -- 0 = - 47.772384 + 5.86k_1 + 2.60 (1) + 3.42 (2) + 2.46 (3) + 2.26 (4)
+ 1.33 (5). . . . . (3)

(Longitude)--0 = + 34.743552 + 1.43k_1 - 14.24 (1) - 11.66 (2) - 6.49 (3) - 4.52 (4)
- 2.67 - (5). . . . . (4)

(Latitude) -- 0 = - 115.811840 + 5.86k_1 + 9.97k_2 + 4.11 (1) + 4.92 (2) + 3.96 (3)
+ 3.76 (4) + 2.84 (5) + 1.52 (6) + 1.25 (7) + 1.16 (8) + 1.36 (9)
+ 1.47 (10) + 1.85 (11) + 1.47 (12) + 1.54 (13) + 1.72 (14) + 0.34 (15)
+ 0.24 (16) + 0.58 (17) . . . . (5)

(Longitude)--0 = + 32.572080 + 1.43k_1 + 0.84k_2 - 38.63 (1) - 36.04 (2) - 30.84 (3)
- 28.87 (4) - 27.01 (5) - 24.33 (6) - 21.35 (7) - 20.52 (8) - 18.23 (9)
- 16.35 (10) - 14.81 (11) - 13.59 (12) - 10.91 (13) - 9.20 (14)
- 6.61 (15) - 4.22 (16) - 2.37 (17) . . . . (6)

In equations (2) and (3), which hold the fixed position of John from Point, the coefficients of k_1 are obtained as in the preceding problems. In equation (5) the coefficient of k_2 is equal to the computed latitude of Mesa minus the computed latitude of John, or (30°50′.77 - 30°40′.80) and the coefficient of k_1 is the computed latitude of John minus the latitude of Point, or (30°40′.80 - 30°34′.94). Similarly, in equation 6 the coefficient of k_2 is equal to the computed longitude of Mesa minus the computed longitude of John, or (88°31′.22 - 88°30′.38) and the coefficient of k_1 is equal to the computed longitude of John minus the longitude of Point, or (88°30′.38 - 88°28′.95).

Dividing equation (4) by 2 and equation (6) by 5 before making up the correlates, produces the forward solution given in Table 5.

The accumulations are made and checked as in the previous problems with the result shown in Table 6.

Table 6--Results of accumulation computations, Point to John to Mesa traverse line

	k_1	k_2	η	Σ	Check
Original normal terms	+ 12.721	+ 10.138	- 133.2980	- 19.2826	. . . .
k_1	- 13.82544	- 3.46205	+ 106.92578	+ 76.91736	- 0.00007
k_2	. . . .	- 43.95733	+ 335.94331	+ 278.38593	- 0.00000
η	. . . .	. . . .	- 3097.82331	- 2521.65621	- 0.00001
Σ	. . . .	. . . .	. . . .	- 2147.07011	- 0.00021

The sum of the squares of the corrections to the angles equals $+ 13.8254k_1^2 + 2(+ 3.4621)k_1k_2 + 43.9573k_2^2 + 2(- 106.9258)k_1 + 2(- 335.9433)k_2 + 3{,}097.8233$. Setting the partial derivatives of this expression equal to zero: $+ 13.8254k_1 + 3.4621k_2 - 106.9258 = 0$; and $+ 3.4621k_1 + 43.9573k_2 - 335.9433 = 0$.

It will be seen that these two equations are symmetrical about the diagonal terms as other normal equations are, and that they may be obtained directly from a table of accumulations.

The solution of these two equations gives $k_1 = + 5.93731$, $k_2 = + 7.17487$ and the factors 1.000013671 and 1.000016521. Using these values for k_1 and k_2 in the back solution; $C_1 = - 9.29527$; $C_2 - 2.57125$; $C_3 = -0.03337$; $C_4 = + 0.82411$; $C_5 = + 0.03538$; and $C_6 = - 2.10092$. The values of the C's and of the k's give the results set forth in Table 7.

The procedure used in this problem may be applied also to those cases in which there is an abrupt change in the general direction of the line, and it is desirable that changes in measured length take up the greater part of the discrepancy in position.

Table 7--Observed and adjusted traverse data, Point to John to Mesa traverse line

Station	Angle		Length	
	Observed	Adjusted	Measured	Adjusted
	° ′ ″	° ′ ″	meters	meters
Big				
Point	194 10 24.6	194 10 25.7	2,081.846	2,081.874
Paul	147 57 45.2	147 57 46.3	4,027.718	4,027.773
Pine	184 55 32.2	184 55 33.3	1,511.890	1,511.911
Hurl	156 57 08.6	156 57 09.6	1,605.986	1,606.008
Pelham	180 07 56.0	180 07 57.0	2,354.708	2,354.740
John	203 53 30.1	203 53 31.1	2,272.218	2,272.256
Mace	179 37 34.2	179 37 33.9	622.238	622.248
Moris	191 58 25.6	191 58 25.0	1,748.489	1,748.518
Harl	178 31 47.7	178 31 46.1	1,420.960	1,420.983
Ton	191 40 59.6	191 40 57.2	1,209.537	1,209.557
Mill	144 19 35.4	144 19 32.4	991.657	991.673
Hub	201 59 38.8	201 59 35.3	2,021.947	2,021.980
Mont	184 53 46.0	184 53 48.1	1,319.837	1,319.859
Tate	140 59 02.0	140 59 03.3	2,302.485	2,302.523
Timer	208 58 02.9	208 58 03.1	1,818.161	1,818.191
Agra	195 34 52.4	195 34 51.6	1,425.578	1,425.602
Price	151 35 44.8	151 35 43.3	1,871.773	1,871.804
Mesa	148 32 12.4	148 32 09.8		
Ward				

Note: This table lists the angles at the station from the station above clockwise to the station below. The lengths are from the station to the station below.

State plane coordinate systems--In the computation of traverse on state plane coordinate systems, in those cases where the field work is of that degree of precision as to justify a least-squares adjustment, a similar procedure may be applied.

The condition equations which hold the fixed x and y on any system of Cartesian coordinates are respectively:

$$0 = (x_2 - x'_2)/\text{Arc } 1'' + (10^p\, \Delta Sg/Sg)(x_2 - x'_1)/(10^p \text{ Arc } 1'') + Q_1\,(1) + Q_2\,(2) + Q_3\,(3) + \ldots + Q_n\,(n)$$

$$0 = (y_2 - y'_2)/\text{Arc } 1'' + (10^p\, \Delta Sg/Sg)(y_2 - y'_1)/10^p \text{ Arc } 1'' - P_1\,(1) - P_2\,(2) - P_3\,(3) - \ldots - P_n\,(n)$$

Where

x_2, y_2 = computed coordinates of the terminal point

x'_2, y'_2 = fixed coordinates of the terminal point

x'_1, y'_1 = fixed coordinates of the starting point

$\Delta Sg/Sg$ = ratio of the change in the grid length to the grid length

10^p = some convenient power of 10

P = summation of the departures from the terminal point

Q = similar summation of the latitudes

It will be noted that these equations are similar to the perpendicular equation used in the adjustment of a traverse loop, as discussed on pages 97 to 99 of the Manual of First Order Traverse, U. S. Coast and Geodetic Survey Special Publication No. 137. The constant terms of these equations also contain the variable element expressing the effect of a constant-ratio change in the length. Since the computation by latitudes and departures is most easily done with the natural functions this element is best expressed directly and not as it has been presented heretofore as a change in the logarithm.

Since there is no convergence of the lines of reference on a grid system it is more practical to correct first the observed angles so that the azimuth closes before beginning any preliminary computations.

Traverse line, Miakka to Bee Ridge--To illustrate the application of these conditions, let us apply them to a line from Miakka to Bee Ridge where Miakka has the fixed coordinates x = 413,046.05 feet and y = 1,047,419.61 feet; and Bee Ridge, x = 373,549.14 feet and y = 1,060,276.14 feet. Also to be held are the two fixed plane azimuths:

Miakka to Miakka azimuth mark = 106°20′08″; and
Bee Ridge to Bee Ridge azimuth mark = 295°26′24″

After correcting the observed angles so that the azimuth closes and converting the measured lengths to the distances on the grid by standard practices, the preliminary computations give the results shown in Table 8.

Table 8--Results of preliminary computations, Miakka to Bee Ridge traverse line

Section		Preliminary plane azimuth	Grid distance	Departure	Latitude
From	To				
		° ′ ″	ft	ft	ft
Miakka	T. P. 1	105 16 38.2	4,100.84	- 3,955.924	+ 1,080.532
T. P. 1	A - 13	106 03 16.3	6,293.94	- 6,048.470	+ 1,740.602
A - 13	B - 13	134 13 04.1	5,710.45	- 4,092.645	+ 3,982.399
B - 13	T. P. 2	134 13 59.7	4,027.28	- 2,885.570	+ 2,809.354
T. P. 2	T. P. 3	109 43 58.0	528.10	- 497.089	+ 178.304
T. P. 3	C - 13	92 31 15.6	1,936.18	- 1,934.306	+ 85.164
C - 13	D - 13	92 24 12.1	4,578.79	- 4,574.762	+ 192.008
D - 13	E - 13	102 24 45.4	5,678.42	- 5,545.687	+ 1,220.578
E - 13	T. P. 4	84 38 15.5	5,103.61	- 5,081.274	- 476.954
T. P. 4	T. P. 5	110 48 05.4	492.18	- 460.098	+ 174.789
T. P. 5	T. P. 6	113 46 16.5	3,609.01	- 3,302.829	+ 1,454.742
T. P. 6	Bee Ridge	110 27 20.5	1,193.55	- 1,118,288	+ 417.125
			Total	-39,496.942	+12,858.643

These preliminary results produce the following three condition equations:

(Azimuth) -- 0 = 0.0 + (1) + (2) + (3) + (4) + (5) + (6) + (7) + (8) + (9) + (10)
- (11) - (12) - (13) . . . . (1)

(x deviation) 0 = - 6,600.4738 - 81,468.2909 ($10^5\ \Delta Sg/Sg$) + 12,858.643 (1)
+ 11,778.111 (2) + 10,037.509 (3) + 6,055.110 (4) + 3,245.756 (5)
+ 3,067.452 (6) + 2,982.288 (7) + 2,790.280 (8) + 1,569.702 (9)
+ 2,046.656 (10) + 1,871.867 (11) + 417.125 (12) . . . . (2)

(y deviation) 0 + 435,837.5357 + 26,522.8551 ($10^5\ \Delta Sg/Sg$) + 39,496.942 (1)
+ 35,541.018 (2) + 29,492.548 (3) + 25,399.903 (4) + 22,514.333 (5)
+ 22,017.244 (6) + 20,082.938 (7) + 15,508.176 (8) + 9,962.489 (9)
+ 4,881.215 (10) + 4,421.117 (11) + 1,118.288 (12) . . . . (3)

With such coefficients it is obvious that in practice the decimal places need not be considered. They are given here to show exactly how they are derived.

Dividing equation (2) by 2000 and equation (3) by 10,000 before forming the correlate equations produces the solution shown in Table 9.

The value of the sum of the squares of the changes to the angles equals + $210.38403k^2$ + 330.09015k + 594.53117. This gives a value of k = -1.56899; C_1 = + 3.39110; C_2 = - 0.11505, and C_3 = - 1.76677.

The correction factor is obtained by subtracting k from the fifth decimal place of unity, or 0.9999843101. Using these corrections, we have the results shown in Table 11.

Table 9--Solution of three condition equations, Miakka to Bee Ridge traverse line

1	2	3	10^5 ΔSg/Sg = k	η	Σ
+ 13.0000	+ 29.3600	+ 23.0400	. . . .	0.00	+ 65.4000
C_1	- 2.258462	- 1.772308	. . . .	. . . .	- 5.030770
	+ 122.1402	+ 82.7056	- 40.7341	- 3.3002	+ 190.1715
	+ 55.8318	+ 30.6706	- 40.7341	- 3.3002	+ 42.4681
	C_2	- 0.549339	+ 0.729586	+ 0.059110	- 0.760643
		+ 61.1500	+ 2.6523	+ 43.5838	+ 213.1317
		+ 3.4675	+ 25.0291	+ 45.3967	+ 73.8933
		C_3	- 7.218198	- 13.092055	- 21.310253

Table 10--Results of accumulation computations, Miakka to Bee Ridge traverse line

	k	η	Σ
Original normal term	+ 38.0818	- 40.2836	- 468.7032
k	- 210.38403	- 330.09015	- 502.39235 - 3
	. . . .	- 594.53117	- 964.90489 - 3
	. . . .	. . . .	- 1936.00034 - 10

Table 11--Observed and adjusted traverse data, Miakka to Bee Ridge traverse line

Station	Angle		Grid length	
	Observed	Adjusted	Measured	Adjusted
Azimuth mark	° ′ ″	° ′ ″	ft	ft
Miakka	358 56 28.6	358 56 25.9	4,100.84	4,100.78
T. P. 1	180 46 36.5	180 46 34.5	6,293.94	6,293.84
A - 13	208 09 46.2	208 09 45.4	5,710.45	5,710.36
B - 13	180 00 54.0	180 00 54.2	4,027.28	4,027.22
T. P. 2	155 29 56.7	155 29 57.5	528.10	528.09
T. P. 3	162 47 16.0	162 47 16.9	1,936.18	1,936.15
C - 13	179 52 54.9	179 52 56.2	4,578.79	4,578.72
D - 13	190 00 31.7	190 00 33.8	5,678.42	5,678.33
E - 13	162 13 28.5	162 13 31.6	5,103.61	5,103.53
T. P. 4	206 09 48.3	206 09 52.3	492.18	492.17
T. P. 5	182 58 09.5	182 58 13.6	3,609.01	3,608.95
T. P. 6	176 41 02.4	176 41 07.2	1,193.55	1,193.53
Bee Ridge	4 59 01.9	4 59 06.9		
Azimuth mark				

Note: This table lists the angles at the station from the station above clockwise to the station below. The lengths are from the station to the station below.

These results will not agree precisely with the data furnished by the United States Coast and Geodetic Survey because the line was adjusted on the spheroid and the above adjustment has been done merely to show the application of this procedure to work computed on state plane coordinate systems. The differences, however, are caused only by the rounding off of the quantities used in the two computations.

Comparison with distribution by compass rule--The least-squares adjustment gives a maximum correction to angle of 5''.0, and an average correction of 2''.4. Distribution by compass rule produces a maximum correction of 13''.0 and an average correction of 5''.0.

Conclusion--In the problems which have been discussed, all of the corrections to the lengths have been within reason. It does not follow that this will always be the case. As this procedure is used in present practice, after an examination of the measurements, a limit is set upon the amount that the lengths may be changed. In those cases where k is excessive this maximum quantity should be assigned to k and the angles allowed to take up the rest of the position discrepancy.

The major theoretical disadvantage of this system is that the corrections to the lengths are based upon the minimum of corrections to the angles. At the same time this very disadvantage furnishes to the engineer a length between two traverse stations which has been changed but slightly and an azimuth that is as close as possible to the observed value.

In the second place the effect of the relationship of the position discrepancy to the direction of progress is more or less automatically taken into account. When the discrepancy is in the general direction of progress, the correction to the lengths will be large, and when the discrepancy is not in the direction of progress, it will be small.

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GRAVITY ANOMALIES AND THE DEFLECTION OF THE PLUMB LINES

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In 1928, F. A. VENING MEINESZ obtained a formula expressing the relation between gravity anomalies and deflections of plumb line. This formula[1], derived from the theorem of STOKES, may be written as in (1).

$$\theta = \frac{\partial N}{\partial \psi} = -\frac{1}{4\pi G}\int_{\Omega} \Delta g \frac{\partial F}{\partial \psi}\, d\varpi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where θ = the total deflection of the plumb line
G = the mean value of gravity on the surface of the Earth
$d\varpi$ = surface element on the sphere of unit radius
Δg = gravity anomaly corresponding to the element
F = STOKES' function, a function of the angular distance ψ between the point where N is to be computed, and $d\varpi$

$$\begin{aligned}\frac{\partial F}{\partial \psi} = -\frac{1}{2}\,\frac{\cos(\psi/2)}{\sin^2(\psi/2)} - 3\cos(\psi/2) + 5\sin\psi \\ + 3\sin\psi \log_e[\sin(\psi/2) + \sin^2(\psi/2)] \\ - \frac{3}{2}\cos\psi \cot(\psi/2)\left[\frac{1+2\sin(\psi/2)}{1+\sin(\psi/2)}\right]\end{aligned}$$

By separating the deflection into two components, one along the meridian and the other perpendicular to it, and substituting the expression $\sin\psi d\psi d\alpha$ for $d\bar{\omega}$, we obtain the meridional and the prime-vertical deflections as in (2).

$$\left.\begin{aligned}\eta &= -\frac{1}{2\pi G}\int \cos\alpha d\alpha \int \Delta g \sin\psi \frac{\partial F}{\partial \psi}\, d\psi \\ \xi &= -\frac{1}{2\pi G}\int \sin\alpha d\alpha \int \Delta g \sin\psi \frac{\partial F}{\partial \psi}\, d\psi\end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where α denotes the azimuth of the element and the limits of integration are $\psi = 0°$ and $180°$ and $\alpha = 0°$ and $360°$.

With these formulas, VENING MEINESZ calculated the deflection for the three stations Urk, Wolberg, and Utrecht, in the central part of the Netherlands, where a gravity survey had nearly been completed. The results were compared with those obtained from an astronomic-geodetic survey, and gave a difference of less than one-half second. The same formula was employed by GULATEE[1], who obtained as the deflection between the stations Kalianpur and Kesri the value 6″.5, while from the astronomic-geodetic connection the resulting value was 6″.8. The agreement is very satisfactory.

For actual use, (2) was transformed as in (3) by GULATEE[1]

$$\left.\begin{aligned}\eta &= -\frac{1}{2G}\sum_{\alpha=0°}^{\alpha=360°}\;\sum_{\alpha=0°}^{\psi=180°} \frac{\Delta\alpha}{2\pi}\Delta\psi\left(\sin\psi\frac{\partial F}{\partial\psi}\right)_M \Delta g_M \cos\alpha \\ \xi &= -\frac{1}{2G}\sum_{\alpha=0°}^{\alpha=360°}\;\sum_{\psi=0}^{\alpha=180°} \frac{\Delta\alpha}{2\pi}\Delta\psi\left(\sin\psi\frac{\partial F}{\partial\psi}\right)_M \Delta g_M \sin\alpha\end{aligned}\right\} \ldots\ldots\ldots\ldots (3)$$

---

[1] VENING MEINESZ, F. A., A formula expressing the deflection of the plumb-line in gravity anomalies, etc., Amsterdam, Proc. K. Akad. Wet., v. 31, No. 3, 1928; the same formula was obtained by B. L. GULATEE in 1934, Surv. India, Geod. Rept., 1934.

in which we consider the Globe as divided into zones bounded by circular rings of width $\Delta\psi$ surrounding the point to be computed and each zone as divided into sectors of angular opening $\Delta\alpha$; the subscript M is used to indicate mean values employed for each zone.

If we denote the function in the parentheses of (3) by Q, then

$$
\begin{aligned}
Q &= \sin\psi \frac{\partial F}{\partial \psi} \\
&= -\frac{\cos^2(\psi/2)}{\sin(\psi/2)} - 3\sin\psi\cos(\psi/2) + 5\sin^2\psi + 3\sin^2\psi\log_e[\sin(\psi/2) + \sin^2(\psi/2)] \\
&\qquad - 3\cos\psi\cos^2(\psi/2)\left[\frac{1 + 2\sin(\psi/2)}{1 + \sin(\psi/2)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)
\end{aligned}
$$

Table 1, which is from GULATEE'S paper [1], gives the radii of the zones and the effects produced by them.

Table 1--Radii of zones and effects produced by them

Radii of zones	$\Delta g\cos\alpha$ or $\Delta g\sin\alpha$	Radii of zones	$\Delta g\cos\alpha$ or $\Delta g\sin\alpha$	Radii of zones	$\Delta g\cos\alpha$ or $\Delta g\sin\alpha$	Radii of zones	$\Delta g\cos\alpha$ or $\Delta g\sin\alpha$
° °	″	° °	″	° °	″	° °	″
1/2 - 1	+ 0.16	10 - 15	+ 0.12	40 - 50	+ 0.09	90 - 100	- 0.06
1 - 2	+ 0.16	15 - 20	+ 0.10	50 - 60	+ 0.06	100 - 120	- 0.14
2 - 5	+ 0.24	20 - 25	+ 0.08	60 - 70	+ 0.02	120 - 140	- 0.11
5 - 8	+ 0.12	25 - 30	+ 0.07	70 - 80	- 0.01	140 - 160	- 0.06
8 -10	+ 0.06	30 - 40	+ 0.12	80 - 90	- 0.04	160 - 180	- 0.01

In Table 1, the values of the first three zones are not exact, as GULATEE took the average of Q for its mean value, which, for inner zones, may differ from the actual one by 0″.02 or 0″.03. The actual mean value may be obtained by integrating the function between the limits and then dividing by the interval. Q contains five terms, the first one of which only changes more rapidly in the inner zones, and we have to perform the integration on this term only. By integrating the first term, we get

$$
\begin{aligned}
\int_a^b \frac{\cos^2(\psi/2)}{\sin(\psi/2)}\,d\psi &= \int_a^b \frac{d\psi}{\sin(\psi/2)} - \int_a^b \sin(\psi/2)\,d\psi \\
&= 2\log_e\tan(\psi/4)\Big|_a^b + \cos(\psi/2)\Big|_a^b
\end{aligned}
$$

The second term of the right-hand side is very small, and for small values of the angle ψ it is practically equal to zero; therefore we may write (5).

$$
Q_M = \frac{-2[\log_e\tan(b/4) - \log_e\tan(a/4)]}{\Delta\psi\ (= b - a)} + \text{(Remaining terms containing the average values of each for } \psi = a \text{ and } \psi = b) \ldots\ldots\ldots\ldots (5)
$$

By this method, the writer obtains for the first three zones of GULATEE'S table, the values 0″.149, 0″.149, and 0″.211, instead of 0″.16, 0″.16, and 0″.24, respectively.

The computations of the deflection by this method are difficult, for we have to make a numerical integration on the product of Q and the gravity anomalies--that is, we have to multiply the values of gravity anomaly of every station by the function Q corresponding to the geodetic position of the station, and then sum the products. Although we may use tables such as Table 1, to facilitate the evaluation of the function Q, the greater part of the computation cannot be avoided. In order to lessen the work a little, the writer proposes use of a diagram (see Fig. 1), analogous to those employed by HAYFORD and BOWIE in the calculations of the topographic and isostatic reductions on the values of gravity. It consists of circles and radial lines dividing the region to be calculated into compartments. These circles and lines are so drawn that each compartment will give a certain effect on the meridional or prime-vertical deflection for every milligal of gravity anomaly. It is constructed on tracing-paper to a scale corresponding to that of the gravity map available. This diagram is placed on the map with its center at the point to be computed, and the central line on the meridional line, and the numbers of milligals of gravity anomaly in each compartment are counted and summed algebraically to get the meridional deflection of the plumb-line. The prime-vertical deflection may be obtained in the same way by turning the diagram 90° to the right, that is, by placing the central line perpendicular to the meridional line.

Theoretically, we have to calculate the effects from the point to be computed to its antipode. In this way, the absolute deflection is obtained. But gravity surveys are too far from complete to allow such a detailed and extensive computation. Nevertheless, the relative deflection can be computed. For this purpose, if the two points considered are not too far from each other, a gravity map covering an area of 25° to 30° square will suffice.

Table 2 gives the inner and outer radii of the zones, beginning with a circle of radius 10′ to the antipode, and numbered from 1 to 13. Each zone, except the last one, gives a total effect on the deflection of 0″.16; the last one gives 0″.06.

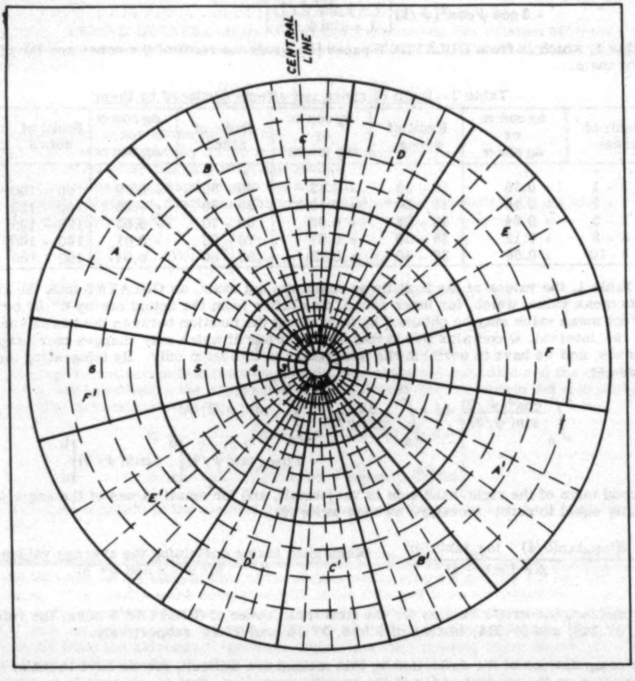

Fig. 1--Diagram for determination of meridional deflection

All zones and sub-zones are divided into compartments. The directions of the radial lines are so fixed that the condition to be fulfilled is 0″.04 $(\Delta\alpha/360°)\cos\alpha = 0''.01$, in which $\Delta\alpha$ is the angular opening of the compartment and α is the azimuth of its central point.

There are 12 compartments in each zone; the zones are lettered A to F and A′ to F′, as shown in Figure 1. Owing to symmetry, only the azimuths of the lines for a quarter of the zones are given in Table 3.

For more detailed work, each compartment is sub-divided into 16 sub-compartments, as shown in dashed lines in Figure 1. In this way, each sub-compartment gives an effect of 0″.01 for every milligal of gravity anomaly. It should be noticed that a positive anomaly in the northern (or eastern) side of the point in question gives a northerly (or easterly) deflection, while for southern (or western) side of the point, the contrary is true.

Table 2--Inner and outer radii of zones and sub-zones and zone effect for one milligal

Zone and sub-zone	Radius Inner	Radius Outer	Effect 1 mgal	Zone and sub-zone	Radius Inner	Radius Outer	Effect 1 mgal
	° ′ ″	° ′ ″	″		°	°	″
1 a	00 10 00	00 12 08	+ 0.16	8 a	19	21	+ 0.16
b	00 12 08	00 14 36		b	21	23	
c	00 14 36	00 17 40		c	23	26	
d	00 17 40	00 21 20		d	26	29	
2 a	00 21 20	00 25 44	+ 0.16	9 a	29	32	+ 0.16
b	00 25 44	00 31 00		b	32	35	
c	00 31 00	00 37 24		c	35	38	
d	00 37 24	00 45 08		d	38	42	
3 a	00 45 08	00 54 20	+ 0.16	10 a	42	46	+ 0.16
b	00 54 20	01 05 20		b	46	51	
c	01 05 20	01 18 36		c	51	58	
d	01 18 36	01 34 56		d	58	71	
4 a	01 34 56	01 53 52	+ 0.16	11 a	71	87	+ 0.16
b	01 53 52	02 16 20		b	87	94	
c	02 16 20	02 43 00		c	94	100	
d	02 43 00	03 14 28		d	100	106	
5 a	03 14	03 51	+ 0.16	12 a	106	111	+ 0.16
b	03 51	04 35		b	111	116	
c	04 35	05 25		c	116	122	
d	05 25	06 23		d	122	128	
6 a	06 23	07 30	+ 0.16	13 a	128	135	+ 0.06
b	07 30	08 42		b	135	143	
c	08 42	10 03		c	143	153	
d	10 03	11 32		d	153	180	
7 a	11 32	13 13	+ 0.16				
b	13 13	15 01					
c	15 01	16 55					
d	16 55	19 01					

Table 3--Azimuths of boundary-lines

Compartment and sub		Azimuths		
		° ′		° ′
C	3	00 00	and	05 45
	4	05 45		11 20
D	1	11 20		17
	2	17		23
	3	23		29
	4	29		36
E	1	36		43
	2	43		51
	3	51		62
	4	62		77

Applying this method to India, the three stations Kalianpur, Kesri, and Ladi, were chosen, and the relative deflections of the last two with respect to the first were computed. Kesri is situated at a distance of 1°40′ north of Kalianpur, and Ladi is at a distance of 1° south of it. The results are shown in Table 4.

Here only six zones were used. The sum of each column gives the absolute deflection up to the sixth zone. The differences between Kalianpur and the other two give the relative deflections. They are shown in the second and third columns of Table 5; the last two columns give those derived from astronomic-geodetic operations. The signs in Table 5 are opposite to those used by the Survey of India.

Table 4--Meridional deflections for stations in India

Zone	Meridional deflections for Kesri	Kalianpur	Ladi
	″	″	″
1	- 1.65	- 0.62	+ 0.65
2	- 1.87	- 0.32	+ 1.35
3	- 0.89	- 0.21	+ 0.61
4	- 1.28	- 0.71	- 0.64
5	- 0.49	+ 0.08	+ 0.68
6	- 1.08	+ 0.87	+ 1.28
Total	- 7.26	- 0.89	+ 3.93

Table 5--Meridional deflections by two methods for stations in India

Station	Absolute	Relative	Absolute	Relative
	″	″	″	″
Kesri	- 7.26	- 6.37	- 9.2	- 6.8
Kalianpur	- 0.89	0	- 2.4	0
Ladi	+ 3.93	+ 4.82	+ 2.7	+ 5.1

Chinese Embassy,
Washington, D. C.

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NORTHEASTERN OZARK EARTHQUAKES

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Abstract--In recent years, instrumentally-determined epicenters of five earthquakes have been located on the northeastern flank of the Ozark uplift. The local distribution of these epicenters shows: (1) The dangers of considering northeastern Ozark seismic activity as arising from geographically delineated seismic districts, and (2) the importance of discussing the earthquakes in relation to the zone of faults and flexures which lies between the Ozark dome and other major tectonic features to the north and east. Interesting structural features are found in the vicinity of the epicenters of individual earthquakes. The epicenters were situated (1) on the limb of the Eureka, Missouri, anticline; (2) adjacent to the faulted Waterloo-Dupo, Illinois, anticline; (3) in the Ste. Genevieve, Missouri, fault zone; (4) in the vicinity of the Moselle, Missouri, fault; and (5) in the large faulted block southwest of the magnetic high near Bourbon, Missouri. Depth of foci of at least five miles is indicated by the distribution of intensities and the character of the seismograms. In this connection the possible shielding effect of the Ozark core invites further study.

Introduction--Some years ago in compiling a seismic history of Missouri, the author [HEINRICH, 1941] attempted to indicate the general distribution of earthquake epicenters in the central Mississippi Valley by classifying them according to seismic districts. The six districts outlined for Missouri were the New Madrid, Saint Marys, Saint Louis, Hannibal, Springfield, and Northwestern Missouri regions. These geographic areas were established after evaluating the instrumental and macroseismic data on the distribution and frequency of Missouri earthquakes which were available in 1940. During the past five years new data have become available from recent earthquakes and more detailed seismological and geological research. The seismograph station at Cape Girardeau, Missouri, inaugurated in 1938, has provided a new source of instrumental data,

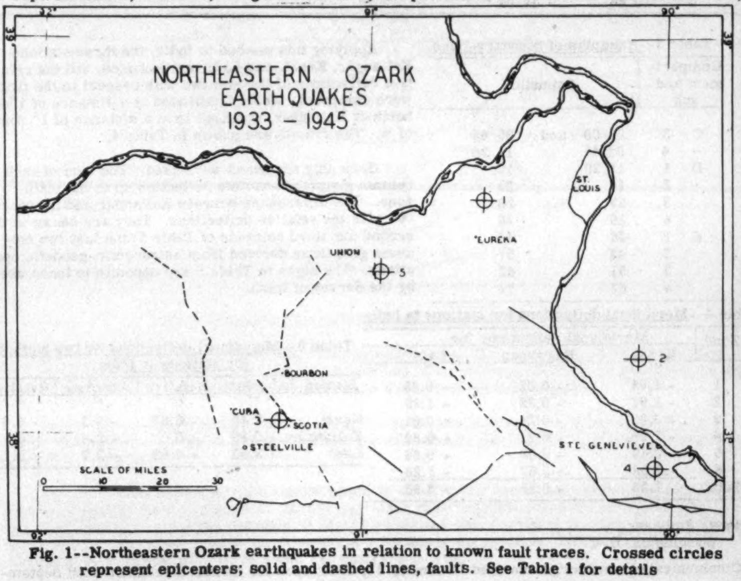

Fig. 1--Northeastern Ozark earthquakes in relation to known fault traces. Crossed circles represent epicenters; solid and dashed lines, faults. See Table 1 for details

and the travel-time tables of WALTER-BIRKENHAUER [1941] have greatly facilitated and increased the accuracy of local epicenter determination. These tables were developed from observational data for earthquakes within 750 miles of a Mississippi Valley seismograph station [WALTER, 1940; WALTER and BIRKENHAUER, 1941]. A study of the new data makes it apparent that the concept of seismic districts in and around Missouri needs some interpretation. It is the purpose of this note to emphasize one aspect of this interpretation.

Data--The locations of five earthquakes which occurred in recent years on the northeastern flank of the Ozarks have been plotted and numbered on Figure 1. Data on four of these shocks have already been reported by various investigators. The information pertinent to the present discussion has been summarized in Table 1. Intensities are on the Modified Mercalli Scale.

Table 1--Northeastern Ozark earthquakes, 1933-1945

No.	Date	Origin time UT	Epicenter		Intensity	Reference
			N. Lat.	W. Long.		
		h m s	°	°		
1	Nov. 16, 1933	13 29 01	38.6	90.6	IV	MACELWANE
2	Nov. 23, 1939	15 14 53	38.2	90.1	V	BIRKENHAUER
3	July 25, 1943	06 49 10	38.1	91.3	IV-V	
4	Sep. 25, 1944	11 37 23	37.9	90.05	II	BUCKIE
5	Mar. 28, 1945	20 45 58	38.4	90.9	III	FRANK

UT: Universal (Greenwich Meridian) time

Under the press of wartime conditions, data for shock No. 3, the earthquake of July 25, 1943, have only recently been assembled by the author. Both preliminary and secondary phases of this earthquake were recorded by the St. Louis and Florissant seismograph stations. Only the secondary phases were recorded by the Cape Girardeau station. The shear phases are particularly strong on all records.

The distance arcs, computed with the aid of the WALTER-BIRKENHAUER tables, were 69.2 miles for St. Louis and 71.3 miles for Florissant. Using a mean origin time of $06^h49^m09.5^s$ UT computed from the St. Louis and Florissant data, the distance arc for the Cape Girardeau station was 106.2 miles. These arcs intersect at approximately 38°.1 N, 91°.3 W. As an indication of the control of these epicenters we might emphasize the values of the epicenter-station distances for the quake of July 25, 1943 as computed from the seismograms and as calculated trigonometrically. The distance from the epicenter to St. Louis as computed from the records is 69.2 miles; as measured 69.1 miles, from the epicenter to Florissant; computed from the records 71.3 miles, calculated 71.4 miles; from the epicenter to Cape Girardeau, computed from the records 106.2 miles, calculated 106.3 miles.

The epicenter of the earthquake of July 25, 1943 was in the Meramec Valley southeast of Cuba and northwest of Scotia, Missouri. Although no complete macroseismic survey was made of the earthquake, a few reports are available. The shock was reported by several people in homes along the Meramec River south of Sullivan, Missouri. There was one report of cracked plaster in a cistern south of Sullivan, and many reported that the shock was accompanied by a loud roar which awakened people. Thus in the epicentral region the intensity would be between IV and V on the Modified Mercalli Scale.

Discussion--The locations of the five earthquakes plotted on Figure 1 are not compatible with the seismic districts as previously outlined. According to such a classification Nos. 1 and 2 would be in the St. Louis zone, No. 4 in the St. Marys region, but Nos. 3 and 5 are unclassified. Thus while these districts are convenient to point out regions of more or less seismicity they should not be interpreted as a classification on the basis of origin. From the viewpoint of origin the shocks of the northeastern Ozark border probably have more in common than is conveyed when they are discussed individually or by segregation into arbitrary geographic districts.

There are many known features of the structural geology of the northeastern Ozark flank which should be considered in attempting to understand the distribution of the epicenters of these earthquakes. An obvious point of departure is to inquire whether these earthquakes show any relation to the Ozark uplift.

The area under discussion is of course only a small sector of the Ozark uplift which is a domed area occupying the southern half of Missouri and extending into northern Arkansas and eastern Oklahoma. This structural feature, which consists of Pre-Cambrian intrusives covered by Paleozoic sediments, is conveniently generalized as a dome but it is not symmetrical in shape, and the details of form are not simple, since local folding and faulting make irregular bulges and depressions in the broad gently domed strata. In general the Paleozoic rocks dip away from the igneous core of the St. Francois Mountains which may be considered as the physiographic expression of the structural center of most pronounced doming.

A very practical but difficult problem for Earth Science is to outline the borders of the Ozark uplift. GRAVES in reviewing the literature on the Ozark structure noted that west and northwest of the center the regional dips are slight so that this border of the dome is not sharp. The southeastern boundary he assigns to the line of contact between the Paleozoics and the younger sediments of the Gulf embayment, where because of general relationships he infers faulting. GROHSKOPF [1946] has recently shown that there are evidences of faulting in the subsurface well data in the Gulf Coastal Plain in southeastern Missouri. It might be well in passing over this point to recall that the southeastern Ozark province is outlined by the most intense earthquakes of the Mississippi Valley region. Considerable evidence has recently been accumulated on the localization of the earthquakes in the New Madrid area and these data will be made the subject of a future paper.

To fix the northeastern Ozark structural boundary is difficult. In this problem the seismological data may be useful to the geologist and vice versa. As more and more geologic data become available; it is evident that folding and faulting, more widespread than heretofore considered, separates the Ozark uplift from other major tectonic features to the east and north. Thus to the east and northeast the Ozark dome is separated from the Illinois basin by a zone which includes among others such features as the Ste. Genevieve fault, the Crystal City fault, and the Valmeyer and Dupo anticlines. To the north the Eureka anticline, the Cap au Gris flexure, the Pittsville anticline, the Moselle fault, and the Bourbon structures are among the features between the Mississippi arch and the Ozark uplift. It is at several geographic locations in this zone that the moderate earthquakes of the type listed in this paper occur.

There are interesting structural features in the vicinity of the individual epicenters: (1) The earthquake of November 16, 1933 was on a limb of the Eureka anticline; (2) the Red Bud, Illinois, earthquake of November 23, 1939 was adjacent to the faulted Waterloo-Dupo anticline; (3) the shock of September 25, 1944 was in the Ste. Genevieve fault region; and (4) the earthquake of March 28, 1945 was in the vicinity of the Moselle fault.

The epicenter of the earthquake of July 25, 1943 is in east central Crawford County, Missouri. Crawford County was the locale for a reconnaissance magnetometer survey by the Missouri Bureau of Geology and Mines in 1931 and 1932 which revealed the presence of the "Bourbon High," one of the most striking magnetic anomalies in the state of Missouri [GROHSKOPF and REINOEHL, 1933]. At the time of this early survey the magnetic high was tentatively correlated by the Missouri Survey with mineralization in a buried igneous porphyry ridge. In 1943 and 1944 the Missouri Survey and the United States Bureau of Mines drilled three test wells in this high, and Pre-Cambrian intrusives with varying amounts of mineralization were encountered at depths between 1400 and 1500 feet [CLARK, 1945].

The epicenter of the earthquake of July 25, 1943 lies about seven miles southwest of this magnetic feature and about a mile or so west and on the downthrow side of the Leasburg fault trace. This location is in the large block dropped between the Cuba fault on the west, the Palmer fault on the south, and the Berryman-Leasburg fault on the east.

It is important to note that no cases of surface faulting produced at the time of recorded earthquakes have ever been reported or found in this area. Other evidence also suggests that the earthquakes of this region, while of a shallow-focus type, did not originate in the shallow depths of those parts of the geologic structures available for observation. However, the association of these epicenters with tectonic features, faults, and flexures, in the sedimentary cover has for some time suggested that both phenomena are related to the tectonics of the crystalline basement. GRAVES [1938] in his recent study of Pre-Cambrian structures strengthened this contention when he found that the structures of the Paleozoic cover and the Pre-Cambrian intrusives show a similar alignment.

It is important therefore to know the depth of foci of these earthquakes. This will require more research. BIRKENHAUER and WALTER [1941] based their travel-time tables on a depth of

focus of five miles and obtained an agreement with the observed data. Moreover their tables seem to check with slight variations with new earthquake data. There is some question, however, of the agreement of the macroseismic data. FRANK [1945] in his study of the shock of March 28, 1945 suggested a greater depth of focus than five miles. One thing is certain: Depth is suggested by the fact that these earthquakes of moderate intensities are felt over a rather large area. In connection with the felt area of these shocks it should be noted that the Ozark core seems to be relatively free of tremors, and it also seems to exert a shielding effect on the vibrations from earthquakes which originate on its borders. The relative quiescence is indicated by the lack of historical records of felt earthquakes in the Ozarks, and the shielding effect has been noted in the data on the distribution of intensities of recent earthquakes.

Summary--In summary then we may report that the distribution of instrumentally-located epicenters on the northeastern flank of the Ozark uplift shows a rather wide scattering in the zone of minor structures between the major regional tectonic features.

Realizing the fact of physical continuity it is better in discussions of the origin of these earthquakes to view the distribution in relation to this transition structural zone. For purposes of relative seismicity, use of geographic districts derived from earthquake-structural relations is satisfactory.

Among the outstanding questions presented by central Mississippi Valley earthquakes which will require more data and research for fuller discussion are: (1) At what depth of foci do these earthquakes originate, and (2) do these earthquakes delineate a relatively quiet block or Ozark core, and if so what is the effect of this core on earthquake waves?

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THE GLACIAL ANTICYCLONE THEORY EXAMINED IN THE LIGHT OF RECENT METEOROLOGICAL DATA FROM GREENLAND--Part I

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Abstract--The glacial anticyclone theory, which WILLIAM H. HOBBS propounded in 1910, is today still the only definitely formulated theory concerning the atmospheric movements that take place over an ice sheet of large extent. It stands chiefly on deductive grounds and contains several features that to climatologists as well as to glaciologists have always seemed questionable. Aside from the need of its verification for scientific reasons, there is now also urgent practical need for reliable information about the weather conditions that prevail over the ice sheet of Greenland, for Greenland lies athwart several of the great air routes of the future. In this paper, accordingly, the glacial anticyclone theory is first analyzed and then confronted with the facts of observation that are now at hand, especially those reported from the fixed meteorological stations which were maintained in the interior of Greenland during the 1930s.

In this, the first part of the paper, the meteorological data from the Eismitte station of the German WEGENER Expedition are reviewed. The second part will cover the areological data of that expedition and the similar material from the other ice-cap stations. The conclusions reached are that there is no evidence of a virtually permanent "glacial anticyclone" centered over the Greenland ice sheet. On the contrary, there is consistent evidence from all parts of Greenland that the weather over the ice sheet is controlled by alternating cyclonic and anticyclonic movements. Cyclonic activity is most intense in southern Greenland and weakest in northern Greenland. The entire ice sheet is supplied with snow brought by rising maritime air masses, not by air descending from the upper troposphere. Aviators need not expect so much as a fifty-fifty chance of meeting with good weather on flights across central Greenland, except for a few weeks in midsummer.

Introduction

The true nature of the atmospheric movements that take place over an ice sheet of vast extent and great height, that govern the climatic conditions in its interior, determine its mode of alimentation, and make possible its continued existence, is as yet only dimly understood. It is a controversial subject upon which more light is desired by scientists engaged in several different fields--notably by climatologists, glaciologists, geologists, and geographers; but, in addition, there is urgent need today of reliable information for practical reasons. The ice sheet of Greenland, the second largest existing on the Earth, lies athwart several of the great air routes of the future. Thousands of airplanes doubtless will fly across its broad icy waste within the next few years. Authentic factual data concerning the weather conditions with which pilots will have to contend at different times of the year therefore are of vital importance, and for the successful forecasting of those conditions there must be evolved a sound conception of the special effects upon the atmospheric circulation over and around Greenland that are produced by the high and cold ice sheet itself.

At present the only definitely formulated theory concerning the influence of the ice sheet upon the atmospheric circulation is the glacial anticyclone theory of WILLIAM HERBERT HOBBS. It was conceived about 1910, when practically no first-hand information about the physical conditions in central Greenland, nor, for that matter, in central Antarctica, was available. Even today the theory stands largely on deductive grounds and it contains features that have aroused skepticism and disbelief among well informed climatologists and geologists. It is pertinent, therefore, to inquire to what extent the theory is borne out by the more recent climatological studies in Greenland, and especially by the systematic observations at the meteorological stations that have been maintained for varying lengths of time on or near the crest line of the ice sheet.

In three recent papers HOBBS [1944 a, b, and c] adduces in apparent support of his glacial anticyclone theory the meteorological records of the ice-cap stations of the German ALFRED WEGENER Expedition of 1929 and 1930-1931, the British Arctic Air Route Expedition of 1930-1931, and the Michigan-Pan-American Airways Expedition of 1932-1933. From these papers the casual reader might gain the impression that the glacial anticyclone theory stands fully confirmed in the light of the data from those ice-cap stations, that, indeed, there can be no further room for doubt as to the existence in Greenland of a virtually permanent anticyclone. But is that really true? Surely no one who has studied closely the meteorological data of those expeditions and has familiarized himself with the considered opinions of those scientists who have reviewed that material, would reach that conclusion. On the contrary, he will be convinced, the present writer believes, that the meteorological work at the three ice-cap stations consistently indicates that no glacial anticyclone, such as HOBBS postulates, exists in Greenland; also, that the reviewers are unanimous on that point [BROOKS, 1935, p. 246; DEMOREST, 1943, pp. 378-379; DOUGLAS, 1939, pp. 149-150; 1940, pp. 395-396; GEORGI, 1932, p. 125; 1933, p. 345; 1935, pp. 211-269; 1939 a, pp. 89-92; 1939 b, p. 224; KOPP and HOLZAPFEL, 1939, p. 276; pp. 309-312; pp. 324-325; LINDSAY, 1935 b, p. 245; LOEWE, 1935 a, pp. 75-76; p. 97; 1935 b, pp. 349-350; 1936 b, pp. 360-376; MANLEY, 1941, pp. 393-394; MATTHES, 1942, pp. 185-187; WATKINS, 1932, p. 482; WEGENER, 1939 a, pp. 99-101; 1939 b, p. 374; 1940, pp. 31-32].[a]

The authors listed, it will be seen, are (excepting DEMOREST and the author) all European. Their unanimity very probably reflects the prevailing thought on their side of the Atlantic regarding the status of the glacial anticyclone theory. If in Europe there be any staunch supporters of the theory, at least in so far as it may apply to Greenland, they apparently have not made themselves heard. Should the present writer have overlooked any, he would appreciate being informed of the fact. In any event, ideas concerning the validity of the glacial anticyclone concept appear to be less definitely crystallized on our side of the Atlantic. Traces of a lingering faith in it still appear in fairly recent discussions of ice sheets, past and present, and there is evidence that the doctrine was still being taught in classes in meteorology during the war. It is a notable fact that the forecasters for the American Air Forces in southern Greenland at first attempted to fit their forecasts to a supposedly predominant anticyclonic circulation.

There is, then, a real and pressing need, it seems to the writer, for more enlightenment concerning the nature of the atmospheric movements that govern the weather on an ice sheet such as that of Greenland. He therefore proposes, first, to give a brief analysis of the glacial anticyclone theory, and then to confront that theory with the factual data, from the ice-cap stations chiefly, that are now at hand.

The glacial anticyclone theory

It should be understood at the outset that the glacial anticyclone theory was conceived at a time (about 1910) when the vast interior of Greenland still was, climatologically as well as geographically, a blank area on our maps. No one as yet had set foot upon the central ice plateau, and the only meteorological data available were furnished by coastal stations, by a few short incursions into the margins of the ice sheet, by NANSEN'S pioneer crossing of the narrow southern extremity of Greenland, and by PEARY'S sledge journeys across the northern slopes of the inland ice. One fact, however, stood out prominently in the accounts of these early explorers--namely, that in all parts of Greenland visited by them the surface winds blow predominantly down slope, from the high interior out towards the coasts. That prevailing down-slope movement of the air PEARY aptly likened to "the flow of a sheet of water" [PEARY, 1898, pp. 233-234]. A gravitational flow it is in fact, a draining off of air cooled by contact with the intensely cold surface of the ice sheet and seeking downward paths by reason of its increased density. To HOBBS that fact must have been clear, for he accepted T. C. CHAMBERLIN'S lucid explanation of the down-slope winds [CHAMBERLIN, 1895], and in his writings he often referred correctly to them as "katabatic" winds; besides, he must have realized that the radially diverging pattern of those winds results from the ovoid shape of the great ice dome; yet upon their radial divergence he predicated the existence of a central anticyclone. He admitted that concerning the distribution of pressure in the interior of Greenland nothing was known at the time of his writing, yet he boldly declared [HOBBS, 1910, p. 99; 1911, p. 146]:

> "Nonetheless, upon the basis of the observed winds in those parts of Greenland which have been traversed, it may safely be asserted that a fixed area of high atmospheric pressure is centered over the Greenland isblink[b], and that the cold surface of this mass of ice is directly responsible for its location."

The glacial anticyclone theory, it will thus be seen, stands in the first place upon a strangely illogical combination of two mutually incompatible ideas. Gravitational drainage winds are sup-

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[a] The following papers were received by the author after his manuscript had been submitted for publication: (1) DORSEY, H. G., Jr., Some meteorological aspects of the Greenland ice cap, J. Met., v. 2, pp. 135-142, 1945; (2) HOBBS, W. H., The Greenland glacial anticyclone, J. Met., v. 2, pp. 143-153, 1945. They will be referred to in the second part.

[b] A Danish word for the whitish reflection in the sky over an ice sheet; here mistakenly used as a synonym of ice sheet.

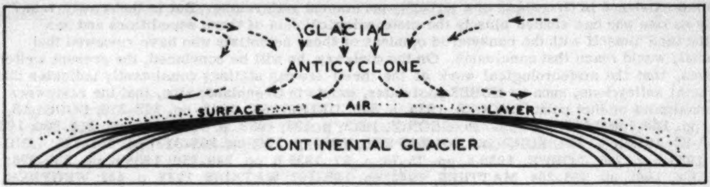

Fig. 1--HOBBS' conception of the structure of a glacial anticyclone and of the lateral growth of an ice sheet by deposition of wind-blown snow at its borders

posed to be also gradient winds emanating from a pressure center. That confusion of ideas pervades all of HOBBS' writings on the glacial anticyclone theory down to the present day.

To follow his reasoning further: The radially-diverging surface winds on a dome-shaped ice sheet must, he rightly argued, be replenished at the center by air flowing in from above. He therefore conceived a circulation in the form of an hour glass [HOBBS, 1944 b, p. 482] characterized by converging air currents at the top, a central down draft, and diverging air currents at the bottom (see Fig. 1). His original statement was [HOBBS, 1911, p. 149]:

"The centrifugal nature of this motion (radial outflow of surface winds) tends to produce a vacuum above the central area of the ice mass, and air must be drawn from the upper atmosphere in order to supply the void. It is here that is located the 'eye' of the anticyclone."

From this statement, however, it appears that HOBBS believed such a circulation to have inherently low pressure rather than high pressure at its center. The term "anticyclone" therefore is not appropriate for it. It is a misnomer, and that fact was pointed out 20 years ago by the British meteorologist HUGH ROBERT MILL in his introduction to HOBBS' book "The Glacial Anticyclones, the Poles of the Atmospheric Circulation" [HOBBS, 1926, p. iii]. MILL was unable to suggest a more suitable term, but he deemed it advisable to warn the reader that HOBBS' definition of an anticyclone differs from that generally accepted by meteorologists.

A circulation of the hour-glass type generated by the intense cold that is produced by outward radiation from an ice sheet domed to great height must, according to HOBBS' theory, have great stability and strength. It must be an almost perpetual structure not easily disorganized by approaching or passing cyclones. His reason for that belief is that the katabatic winds, though feeble on the faintly convex crown of the ice dome, gain speed as they descend its progressively steepening slopes and attain great force at its abrupt margins, at times even hurricane force. They thus form an outward-blowing system of sufficient strength to prevent approaching cyclones from invading the interior of the ice sheet. An entire essay HOBBS has devoted to marshaling proofs in support of his contention that cyclones are unable to reach the center of the Greenland ice sheet, let alone passing clear across it [HOBBS, 1944 a]. Cyclones arriving at the west coast of Greenland, he asserts, are halted there and deflected northward up Davis Strait [HOBBS, 1944 b, p. 482]. In summer the deeper ones may invade the ice sheet to "a maximum distance of some tens of miles" [HOBBS, 1944 a, p. 95]; but he is willing to concede that in southern Greenland they may intrude somewhat farther, through "a marginal strip of as much as 100 miles" [HOBBS, 1944 b, p. 489]. In winter, however, when the katabatic winds are strongest, "the glacial anticyclone controls completely" [HOBBS, 1944 a, p. 82].

If these assertions are to be taken literally, we must suppose that the marginal strip is the only part of the Greenland ice sheet that receives any cyclonic precipitation. However, as HOBBS defines that strip as being limited on its inner side by the névé-line [HOBBS, 1944 a, p. 83], it coincides with the zone of preponderant wastage, where all the snow that falls, and much old ice in the bargain, melts away annually. According to the theory, then, no snow from maritime air masses ever is incorporated in the ice sheet. What, then, it may be asked, aliments the ice sheet and maintains it in existence? What accretions of snow or ice at its surface annually compensate, at least approximately, the enormous losses which it suffers at its margins, by melting, evaporation, deflation, and iceberg calving? It is, HOBBS assures us, the moisture that is brought down from the upper troposphere by the central down-draft in the glacial anticyclone. This is a cardinal point in the theory, which he stresses in many of his writings [HOBBS, 1911, pp. 158-159; 1926, pp. 52-54]. The fine ice needles from the cirrus clouds are dissolved by adiabatic heating in their descent, but when, in contact with the ice surface the air again is cooled below the saturation point, the water vapor contained in it is transformed by sublimation into minute ice spicules, or is condensed on the ground in the form of rime [HOBBS, 1944a, pp. 90-91]. It is these seemingly insignificant hydrometeors that produce the layer of powdery snow that generally covers the central ice plateau; it is by them solely that the huge mass of the ice sheet is supposed to be nourished and built up.

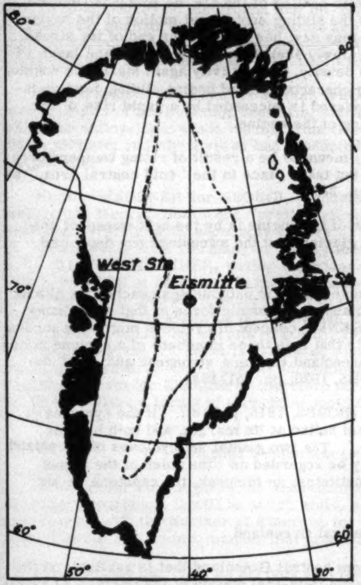

Fig. 2--Map of Greenland showing positions of the three meteorological stations of the WEGENER expedition and the "cold central area" as delimited by HOBBS

These forms of alimentation, moreover, are supposedly restricted largely to a relatively small and sharply defined central strip extending along the main divide, "the cold central area of strong outward radiation" (Fig. 2), where the down draft in the glacial anticyclone descends [HOBBS, 1944 a, pp. 84-87; 1944 b, p. 486]. From this central area, which comprises only about one-quarter of the entire superficies of the Greenland ice sheet [HOBBS, 1941, p. 98], the powdery snow is swept and distributed over the surrounding three quarters of the ice sheet, and even beyond its borders, by the persistent katabatic winds, which act like a huge "centrifugal broom" [HOBBS, 1915, p. 198; 1944 a, pp. 83-84]. By far the greater part of the ice sheet therefore is supplied exclusively with second-hand snow that has drifted down from the "cold central area," there being no direct snow precipitation anywhere except, as stated, in the marginal zone below the névé-line.

The immense volumes of "drift snow" that are almost ceaselessly blown down-slope by the katabatic winds have indeed been remarked upon by every traveler in Greenland or Antarctica. HOBBS refers to the wind drift as "a stupendous phenomenon" [HOBBS, 1944 a, p. 84] and ascribes to its action even the shaping of the ice sheets as flat domes steepening gradually toward their margins. During periods of active glacier growth, he insists, further, ice sheets are built out laterally by the deposition of the bulk of the drift snow at and around their borders [HOBBS, 1911, p. 288; 1915, pp. 199-200; 1944 a, p. 96] and thus they expanded over increasingly large territories (Fig. 1). And all of these stupendous masses of drift snow, he would have us believe, come from the "seemingly inexhaustible supply" [HOBBS, 1943, p. 18] within the small "cold central area," which alone receives first-hand alimentation from the atmosphere. One can not help marveling at the intense concentration of ice spicules and hoar frost in that fabulous inner region which is implied in that strange conception. Unfortunately HOBBS does not back up his assertions with quantitative estimates based either on actual measurements or on theoretical considerations.

It seems a bit inconsistent, furthermore, that in spite of the alleged concentration of alimenting moisture in the "cold central area" of Greenland, that area is said to be blessed with almost perpetual fair weather at the center of the glacial anticyclone. HOBBS depicts it as a "region of calms and light airs" [HOBBS, 1926, p. 77] from which blustering cyclones are forever debarred, where only thin "fog" banks yielding ice spicules float occasionally over the ice surface, the sky overhead being usually clear, or veiled at most by cirrus or cirrostratus clouds [HOBBS, 1911, p. 159]. Such ideal weather conditions might well delight the heart of an aviator. Still, it seems difficult to understand how under such serene weather conditions there could be enough wind to start the huge quantities of drift snow going.

On the slopes of the ice sheet outside the central area the weather is stated to be less steady, for the katabatic winds there gain in strength and, in addition, develop a pulsating habit resulting in alternating calms and fierce gales--"strophs," "surges," or "pulses," as HOBBS has in turn called them. At the margins of the Greenland ice sheet these periodic blows often assume the characteristics of "foehn" winds, owing to the adiabatic heating of the air in its swift descent from altitudes of 9,000 or 10,000 feet to sea-level [HOBBS, 1911, pp. 149-150; 1915, pp. 201-202].

The temperature of the air, even in mid-winter, then rises well above the freezing point, and as a result the snow on the coastal mountains disappears as if by magic, chiefly by evaporation.

Most of the weather-wise observers in Greenland associate these warm foehn winds with the arrival of cyclonic disturbances off the coasts, but HOBBS regards them as an inherent feature of the mechanism of the glacial anticyclone. The adiabatic heating of the air, he contends [HOBBS, 1911, p. 287], "gradually damps and eventually stops the sliding centrifugal motion of the surface air layer. Thus the engine comes to rest, or, as we may say, has reached the end of its stroke. The great calm which ensues allows heat to be again slowly abstracted from the surface layer of air, thereby lowering its temperature and raising its density, until gravity again starts the engine, which now acquires the steadily accelerating velocity characteristic of bodies sliding down on inclined planes. The tempest which is eventually engendered is succeeded by a rapid rise of air temperature, a fall of fresh snow, and another stopping of the engine."

The fall of fresh snow mentioned is not, however, meant to be a result of rising temperatures and foehn conditions at the margins of the ice sheet, but takes place in the "cold central area," as is evident from the following passage [HOBBS, 1911, p. 287]:

"The snow deposited, as it were, between strokes of the engine is by the next sweep of the broom brushed clear from all central portions of the glacier, and the sweepings are deposited near and about the margins of the mass."

HOBBS further conceives that whenever one of these katabatic outpourings reaches its climax just when a cyclone is approaching the coast of Greenland, the dynamic force of that disturbance will be greatly intensified. Adapting this idea to BJERKNES' concept of cyclones migrating across the Atlantic in "families," or series, HOBBS suggests that it is those members of a cyclone family that have been thus rejuvenated at the east coast of Greenland that are strongest and most destructive when they reach northwestern Europe [HOBBS, 1926, pp. 151-154].

In an earlier paper, he stated the idea as follows [HOBBS, 1915, p. 218]: "if the cyclones really advance toward the anticyclone, they are at least halted at its margin, and both become parts of a system of exchanges planetary in its scope." The two glacial anticyclones of Greenland and Antarctica, accordingly, he believes may properly be regarded as "the poles of the atmospheric circulation," and that grand generalization constitutes, so to speak, the capstone of his theory.

The actual weather in central Greenland

The most valuable body of meteorological data from central Greenland that is available at the present time is to be found in the records of the Eismitte (Mid-Ice) station of the German ALFRED WEGENER Greenland Expedition of 1929 and 1930-1931. It is therefore to those records that we turn first.

Eismitte was located close to the geographic center of Greenland, in latitude 70°53'.8 N, longitude 40°42'.1 W (see map, Fig. 2), and at an altitude of about 10,000 feet. It was operated continuously for an entire year--from August 1, 1930, to August 5, 1931. Simultaneously with Eismitte two other well-equipped meteorological stations were operated by the WEGENER Expedition--the West station (and main base), which was established on the western margin of the ice sheet, above the head of Kamarujuk Fiord, at an altitude of 3100 feet; and the East station, situated on the coast of Jameson Land, north of Scoresby Sound, and 75 miles from the outer east coast. Eismitte lay roughly midway between, 248 miles from West station, and 350 miles from East station. All three stations were close to the 71st parallel, and they were supported by two auxiliary stations at and near the west coast and a third at the mouth of Scoresby Sound on the east coast. The whole system was planned by WEGENER with a view to obtaining an "aerological cross-section through the glacial anticyclone" [GEORGI, 1935, p. 191].

To the Eismitte station in particular, WEGENER assigned the task of investigating the weather conditions at the supposed center of the glacial anticyclone. To that end the station was intended to be located directly on the main ice divide, but, as was discovered later, when the triangulation party brought sea-level elevations up from the west coast, it lay actually a considerable distance, perhaps as much as 100 miles, to the west of the divide. This was due to the fact that the party which established the station was unable by aneroid and visual estimates alone to find the highest point on the broad and gently undulating ice plateau.

It can not be said, however, that the actual location of Eismitte was detrimental to the fulfillment of its task. On the contrary, it is, in retrospect, seen to have been distinctly advantageous, for, had the station been located 100 miles farther to the east, it would have been less than 200 miles from the nearest part of the east coast of Greenland and thus well within the sphere of influence of the cyclones that travel up along that coast. As it was, Eismitte lay about an equal distance, about 300 miles, from the nearest parts of the east and west coasts, and definitely within the "cold central area" as delimited by HOBBS. The value of its meteorological data therefore can not be impugned on the ground that the station was not centrally located. There is little reason to doubt that the data obtained at Eismitte are truly representative of the conditions that actually exist in the interior region where, according to HOBBS' theory, the down-draft in the glacial anticyclone descends and aliments the ice sheet with moisture brought down from the upper troposphere.

For director of the Eismitte station, WEGENER chose JOHANNES GEORGI, a distinguished meteorologist of the Deutsche Seewarte, who was keenly interested in the question of the extent to which the anticyclonic winds issuing from Greenland may affect the weather conditions on the North Atlantic, and who already had conducted aerological studies in the area between Greenland and Iceland.

Neither WEGENER nor GEORGI, it should be added, started out prejudiced against the glacial anticyclone theory. Both were "pretty well sold" on the idea, but as good scientists they were desirous of verifying it, especially in view of its bearings on the practicability of the maintenance of "an air route from Germany to North America via Iceland and Greenland" [K. WEGENER, 1940, p. 1]. ALFRED WEGENER, having experienced much good weather on his crossing of Greenland with J. P. KOCH in 1913, was in fact persuaded of the essential soundness of HOBBS' theory--so much so, that he deemed it unnecessary to equip the Eismitte station with an anemograph. At the center of the glacial anticyclone, he argued, there should be so little wind that such an instrument would yield no satisfying results [GEORGI, 1935, p. 193]. But he did have misgivings about HOBBS' conception that the ice sheet is alimented wholly with ice spicules and rime derived from the air which the down-draft in the glacial anticyclone brings down from the cirrus clouds. In his research program for Eismitte he therefore stressed the importance of systematic measurements on all the different forms of alimenting moisture, including "ordinary snow" [WEGENER, 1933, p. 5].

GEORGI'S experiences with the weather at Eismitte

Although for our purpose, the instrumentally registered data of the WEGENER Expedition are of prime importance, it will be worth while, nevertheless, to note first some of GEORGI'S personal experiences with the weather at Eismitte, for those experiences, it is believed, bring home the stark facts of reality in a manner that precludes any possible doubt or denial.

When on July 30, 1930, he arrived with his sledge party at a point 400 kilometers (248 miles) from the west base and decided there to establish the Eismitte station, the weather was bright and almost calm. He consequently believed himself to be at last in the "region of calms and light airs," as HOBBS has so often portrayed it, at the center of the glacial anticyclone; nor did he dread being left alone for two weeks with only a tent for shelter, while the sledges returned to their base and pending the arrival of the next sledge party with supplies. But disillusionment was not long in coming.

"The weather was the biggest disappointment," he wrote [GEORGI, 1939 a, pp. 89-93]. "It broke on my third day at Eismitte, and between then [August 3] and August 18, when LOEWE arrived with the second sledge party, I had only four really clear days; snow fell on ten days. This was quite contrary to expectation, for the Eismitte station was specially intended to investigate the 'glacial anticyclone' . . . . of course, we did not expect to have anticyclonic weather all the time, for on all previous crossings of Greenland bad weather had been encountered from time to time in the interior of the ice cap . . . we did, however, expect that depressions would occur only as transient interruptions of the fine weather, whereas we seemed to get just the opposite, prolonged depressions only occasionally interrupted by fine weather . . .

" . . . That night [August 18] the wind was strong and gusty (clearing wind from the NE, according to his day-to-day record) and the temperature fell to -31°F . . . Two days later there was a fierce blizzard from the SSW and a heavy fall of snow--deep snowdrifts everywhere, apparatus snowed up inside and out, and the big balloon cellar (which, with great exertion, he had excavated in the hard firn) drifted full of snow. 'Where's the anticyclone?' I groan in my diary. It was not until the following day that I laboriously cleared a way through the loose snow to the barometer. After days of work I eventually cleared out the balloon cellar and built a wall six feet high around it to keep back the drifting snow."

The drifting snow from which he sought protection was, however, not primarily that which was being swept down-slope in moderate quantities by the easterly katabatic winds, but that which was being hurled in northerly directions, at right angles to the slope, by the violent southerly storm winds. Already on his sledge journey to Eismitte, GEORGI had noticed that the sastrugi cut by the wind in the hard old snow on the ice-plateau trend, as a rule, in northerly or northwesterly directions. He therefore placed the entrance to his circular bulwark on the north side, changing it later to the northwest side [GEORGI, 1935 b, p. 198]. Even so, his balloon cellar soon drifted full again, and he was unable to keep it cleared during the entire seven winter months (September 16, 1930, to April 15, 1931.)

The snow that fell during those storms, it need hardly be said, was real snow, no mere ice spicules or rime. Rime actually was frequently deposited during the nights, but only in minute quantities; and ice spicules produced by sublimation from supercooled air occurred only on clear days. In his day-to-day entries, GEORGI carefully distinguished between these three different types of hydrometeors, representing them by separate symbols. The ice spicules he denotes, playfully, as "diamond dust, fine crystals out of a clear sky" (Diamantstaub, feine Kristalle aus heiterem Himmel) [GEORGI, 1935 b, p. 211].

The adverse weather conditions which GEORGI experienced during his first three weeks at Eismitte proved to be no unusual spell. In September the snow storms became more persistent and severe, while during the intervals of fair weather the temperature sank lower and lower. GEORGI and SORGE, the glaciologist, who had arrived meanwhile, still managed to live in the tent, but when on October 5 the thermometer went down to - 40°F, and five days later to - 62°F, they decided to dig in and live underground. Winter had set in, and there was no further hope that the lumber for their hut would be brought up. (The motor sledges loaded with the lumber were snowed in, about the middle of September, near the half-way point, about 125 miles from the west base. They were stalled, not merely by drifting snow but by a howling blizzard--one of those cyclonic storms which, according to HOBBS' positive assertions, do not penetrate beyond the marginal zone of the ice sheet, especially in winter, when, he claims, the glacial anticyclone reigns supreme.) The two men at Eismitte, finding that they had adequate supplies, and enough fuel (paraffin) to keep their ice cavern at a bearable temperature, resigned themselves to stay the entire winter.

Bearable is a relative term. At the floor of their living room the temperature never rose above 5°F, and on the table it never exceeded 23°F [SORGE, 1939, p. 187]. To make the place any warmer would have caused the roof to melt. At meal times, therefore, or when working at the table, the men had to sit in their sleeping bags. In the storeroom, which was kept tightly shut, the temperature usually was close to - 22°F, and at a depth of 54 feet below the surface the thermometer throughout the year stood at - 19.°57F. There the wave of summer heat descending through the firn died out.

Some conception of the winter weather outside may be obtained from SORGE'S description of GEORGI'S usual morning round to the instruments [SORGE, 1939, p. 185]:

"He would come back often shouting cheerfully, 'New cold record, - 68°F, not much wind.' Often, however, he would come back covered with snow and complaining of 'Disgusting weather, only - 13°F, and a 29-mile-an-hour wind. Who was it that told us about the fine weather in Greenland?' "

To sum up: From these informal accounts, it is unmistakably clear, even without supporting statistics, that in central Greenland, in latitude 71°N, snow storms come at frequent intervals, in summer as well as in winter. Those storms are brought by violent southerly winds, which disorganize the down-slope flow of the katabatic winds. The snow that falls is real snow and manifestly constitutes the main nourishment of the ice sheet--ice spicules and rime contribute very little. It is evident, further, that on the central ice plateau, the southerly storm winds, not the down-slope winds, are the most effective "snow broom" and tend to keep the snow at the higher levels. HOBBS' "cold central area" enjoys fair weather only during intervals between storms; its weather conditions are not persistently, or even prevailingly, anticyclonic.

The Eismitte weather records

GEORGI'S meteorological records from the Eismitte station are published in full in volume 4, part 1, of the reports of the WEGENER Expedition [GEORGI, 1935] and, what is especially helpful to those who would study them, they are supplemented by a set of diagrams and graphs four feet long (in pocket of volume), representing graphically all the variations in temperature, pressure, wind velocity, wind direction, and cloudiness, as well as the falls of snow and instances of strong snow drifting, that were observed in the course of a year--from August 1, 1930, to August 5, 1931,

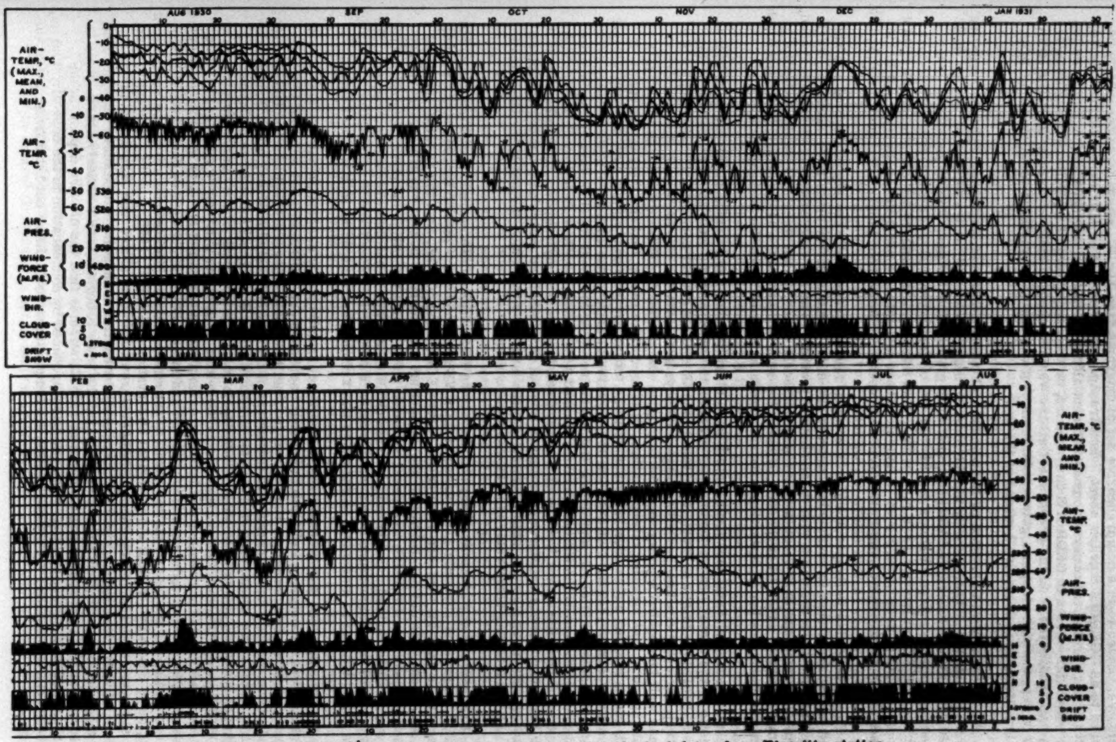

Fig. 3--GEORGI'S graph sheet showing the meteorological data of the Eismitte station inclusive. Added to this comprehensive set of diagrams (see Fig. 3), which hereafter will be referred to as "GEORGI'S graph sheet," is a transparent oversheet on which are indicated the results of his aerological observations at different altitudes. Even if one does not care to examine the individual entries in GEORGI'S daily record, or the many pages of tabulations that follow it, one can readily trace on the graph sheet all the weather changes that occurred at Eismitte from day to day, and can also, at a glance, obtain an overall view of the climatic conditions that prevailed during the successive seasons of the year.

At once the eye is arrested by the phenomenal ups and downs of the temperature curve during the winter months. These are by far the most striking features of the entire record. Rises of 20° to 29°C in 24 hours occurred 16 times, and much greater fluctuations, both up and down, took place in two to five days. From a low of - 59°0 C on January 8, 1931, the temperature rose to a high of - 14°7 C on January 13 (a rise of 79°7 F in five days); by January 16 it again had fallen to a low of - 54° C (a drop of 89°3 F in 78 hours). These are extreme examples, it is true, but fluctuations of the same general amplitude occurred repeatedly throughout January, February, and March.

Each great rise in temperature, it is evident, further, came when the sky clouded up and the wind veered from east to south-southeasterly and south-southwesterly directions. Almost invariably, too, snow storms came with those southerly winds. The low temperatures, on the other hand, occurred during spells of clear weather with northerly winds, which were soon replaced by the normal katabatic winds from the east. During the summer season the temperature fluctuated much less, and more gradually, apart from the very regular diurnal rises due to insolation.

In the sharp alternations of extremely cold, clear weather and warmer cloudy weather characteristic of the winter season (he does not mention the snow storms) HOBBS, ever faithful to his thesis, professes to see a "sort of rhythm in the Greenland glacial anticyclone" [HOBBS, 1944 c, p. 491]. He detects a long period averaging 23 days and a shorter one of about 6-1/2 days. But it may well be doubted whether any meteorologist who studies the Eismitte records objectively would agree to that amazing interpretation. It is much like saying that the alternating spells of cold, clear weather and milder stormy conditions (characteristic of a typical New England winter) are merely rhythmic phases of a sort of temperamental anticyclone that hovers perpetually over the northeastern part of our continent. But surely not even the most loyal Bostonian would pretend that his corner of the United States is blessed with almost constant anticyclonic weather. As a matter of fact, the winter weather in central Greenland is in many respects analogous to that in New England. The main difference is that in central Greenland the entire scale of temperatures is lower. Whereas New England in winter is often favored with a thaw, the top of the Greenland ice cap has freezing temperatures at all times in winter.

It is interesting to note, further, that the strong fluctuations in temperature at Eismitte which HOBBS regards as rhythmic are classed by LOEWE as "aperiodic" [LOEWE, 1935 a, pp. 82-84]. Inasmuch as LOEWE wintered at Eismitte, with GEORGI and SORGE, kept the records for those two observers, and did practically all the computing, his judgment in these matters must surely be better than that of HOBBS, who never ventured more than a few miles in upon the margin of the ice sheet. It is, indeed, readily evident from GEORGI'S graph sheet that the intervals between the high peaks of the temperature curve vary greatly in length. In autumn and in mid-winter they range from three days up to nine days; in February and March they range up to 16 and even 22 days.

HOBBS points out that "these rises in temperature are closely associated with an increase of the cloud cover," outgoing radiation then being "screened out" [HOBBS, 1944 c, p. 491]. That explanation is correct as far as it goes, but it is not the whole story. It overlooks the fact that the cloud cover spreads and thickens with the advent of the southerly storm winds, which disorganize the feeble katabatic winds; also, that the temperature rises directly with the force of the storm winds and promptly drops when those winds die down. Each high peak of the temperature curve on GEORGI'S graph sheet, in fact, coincides exactly with a peak of the wind-force curve. That coincidence deserves to be stressed, for it indicates unmistakably that the stronger the southerly storm winds are, the most completely do they disrupt and sweep away the stratum of cooled air that normally overlies the surface of the ice sheet. That stratum is at Eismitte only a few hundred meters deep, as is shown by GEORGI'S aerological observations [GEORGI, 1935, p. 378]. It follows, then, that at the top of the ice sheet, rises in temperature of 20° to 40°C are due largely to the invasions of warm maritime air and not merely to obstruction of outgoing radiation by clouds. That this must be so is indicated also by the fact that the snow brought by the southerly storm winds is not less than 7°C, and sometimes as much as 11°5 C, warmer than the old firn deposit in the ice sheet [LOEWE, 1938, p. 701]. Were the snow produced by condensation in the cold-air stratum, as the glacial anticyclone theory postulates, its temperature would differ but little from that of the ice sheet.

Atmospheric pressure at Eismitte, it is evident from GEORGI'S graph sheet, also fluctuates most strongly in winter and least in summer. As a rule the highs and lows of the pressure curve are related to the periods of clear weather and stormy weather in the manner that is familiar to us in the zone of prevailing westerlies; but the graph shows occasional exceptions to the rule, the barometer rising with the oncoming of a warm front (as from September 29 to October 1, 1930, and from January 26 to February 1, 1931) and falling to low levels during spells of cold and mostly clear weather (as from November 4 to November 8, 1930, and from February 3 to February 10, 1931). At such times the temperature and pressure curves rise and fall together. So far as the writer knows, these anomalous instances have not been adequately explained, either by the meteorologists of the WEGENER Expedition or by those who have reviewed the Eismitte records. To the writer it seems probable that they reflect the as yet little-understood influence of the cold-air stratum, whose pressure upon the surface of the ice sheet varies in some measure independently of the movements in the free atmosphere above it.

However that may be, it is highly significant that the normal pressure fluctuations at Eismitte are of considerable amplitude throughout the year. During the winter months they often amount to 20 or even 25 millimeters (GEORGI used a cistern barometer); and according to LOEWE'S calculations, the monthly means of the day-to-day variations range, in January, up to 6.0 mm and in November up to 6.9 mm. In summer they decline to about 3 mm, but even then they still equal the monthly means at Danmarkshavn and at the base station of the British Arctic Air Route Expedition near Angmagssalik, on the east coast of Greenland [LOEWE, 1935 a, p. 75]. The mean for the entire year at Eismitte is but little lower than at either of those coastal stations, which are situated in close proximity to a regular cyclone path; it is just as great as the annual mean at McMurdo Sound, in Antarctica. LOEWE therefore feels justified in concluding that "these pressure conditions certainly are not characteristic of a persistent high-pressure area" [ibid, p. 76]. In his address before the Royal Meteorological Society he summed up the situation in these words: "At Mid-Ice pressure conditions are not more stable than in central Europe, with its prevailing cyclonic weather" [LOEWE, 1936 b, p. 375].

Inspection of GEORGI'S graph sheet, further, can not fail to impress one with the relatively high frequency and the long duration of the stormy periods at Eismitte, and the relative scarcity and brevity of the good-weather periods. During the seven winter months (September 16 to April 15) no fewer than 48 snow storms and snow flurries were recorded. Snow fell on 121 days out of a total of 212 days. In other words, bad weather prevailed 57 per cent of the total time. Most of the snow storms lasted from a few hours to three or four days, but seven of them continued, with only occasional interruptions, for periods of six to 11 days. Good weather--counting not merely clear days, but all days on which no snow fell--occurred on only 91 days, or 43 per cent of the total time. There were about 33 separate spells of good weather, but of these the majority lasted only from part of a day to three days; eight of them lasted four to six days; an exceptional one, from December 23, 1930, to January 1, 1931, lasted ten days.

Since the storms were accompanied, as a rule, by strong winds (20 to 40 mi/hr) from southeasterly, southerly or south-southwesterly directions, and since clear weather came usually with light northwesterly, northerly, and northeasterly winds, it is no exaggeration to say that throughout the winter season the winds blew from every point of the compass, leaving the katabatic winds only occasional intervals in which to flow down-slope unhindered. Indeed, it is manifest from the aerological oversheet attached to GEORGI'S graph sheet, as well as from his day-to-day record, that at Eismitte the katabatic winds in winter, far from playing the dominant role, functioned only intermittently, when the fine weather permitted. Instead of ruling the weather, as a manifestation of a central glacial anticyclone, they were only a subordinate phenomenon dependent upon favorable conditions in the free atmosphere above the ice sheet. HOBBS' dictum that "in winter the glacial anticyclone controls completely" [HOBBS, 1944 a, p. 82] thus is utterly refuted by the observations that were made at Eismitte. In central Greenland winter is actually the season of most unstable weather conditions, it being the time of most intense cyclonic activity. That fact was set forth clearly by LOEWE ten years ago in his chapter on "Das Klima des grönländischen Inlandeises" in Köppen-Geiger's "Handbuch der Klimatologie" [LOEWE, 1935 a, p. 99]. Is it possible that HOBBS has not seen that masterly treatise? In none of his recent writings does he refer to it.

The glacial anticyclone theory was based originally upon the reports of NANSEN'S and PEARY'S expeditions, which were made in summer; and subsequently HOBBS has sought confirmation in the reports of other summer expeditions, notably those of DE QUERVAIN, in 1912, and of KOCH and WEGENER, in 1913. The theory therefore might be expected to fit at least the pattern of the summer conditions on the Greenland ice sheet. But even that it does not do. As is evident from GEORGI'S account of the stormy weather which he met with at Eismitte in early August, the summer weather in central Greenland is apt to be just as variable as that in winter, though of course, much less severe because of the strong insolation. The graph sheet reveals that no fewer than 31 separate snow storms occurred during the five summer months (April 16 to September 15). Snow fell on 87 days out of 153--that is, on 56.8 per cent of the total number of days, nearly the same percentage as in winter. Most of the summer storms were light and brief, but some of them, such as that on August 20, 1930, which filled GEORGI'S balloon cellar in one night, attained blizzard-like violence. Even in May, June, and July, the best months, there were stormy periods that lasted four to five days at a stretch.

Good weather, including the cloudy days on which no snow fell, occurred on only 66 days, or 43.2 per cent of the total number of days; and of these only 16 were wholly clear or largely so. The spells of good weather lasted usually from one to four days, a few lasted five or six days. Two much longer spells were recorded--one of 13 days, from September 3 to September 15, 1930, and one of 17 days, from May 26 to June 12, 1931. The latter afforded unquestionably the nearest approach to persistent anticyclonic conditions with prevailingly high pressure, although it was interrupted by two snow flurries on June 7.

Comparison of the weather record of Eismitte with the records of the coastal stations of the WEGENER Expedition shows that in summer Eismitte actually had fewer days of clear weather than West station, the ratio being 16 to 26; but it had the same number of clear days as East station. In winter, on the other hand, Eismitte had far more clear weather than either of the coastal stations; it had 50 clear and mostly clear days, whereas East station had only 20 such days and West station only 15 [KOPP and HOLZAPFEL, 1939, pp. 310-311]. Those two meteorologists (who had charge of the East and West stations respectively) find that, taking the average for the entire year, Eismitte was not much more favored with fine weather than either of the coastal stations. Its clear days exceed those at East station by only four per cent, and those at West station by only one per cent [ibid, p. 309].

Cloudiness at Eismitte averages during the year between 5/10 and 6/10. The mean therefore is "not very different from that of the outer coasts of Greenland or of central Europe" [LOEWE, 1936 b, p. 367]. Nor are the clouds at Eismitte merely of the cirrus and cirrostratus types, as HOBBS would have us believe. "Nearly all the cloud forms that we know from temperate latitudes are met on the ice cap; only forms of strong convection, cumulus and cumulonimbus, are rare or missing" [ibid, p. 367]. During storms, with southerly winds, "the cloud cover comes down to the ground" [ibid, p. 371]; Eismitte then is in what appears to be a thick fog, but really in the lower cloud zone. Surely these facts do not bear out HOBBS' contention that the central portions of Greenland enjoy prevailingly clear weather under the influence of a well-nigh perpetual anticyclone.

Neither are HOBBS' repeated assertions regarding the predominance of "calms and light airs" in the "cold central area" on the crown of the ice sheet borne out by the Eismitte records. Summarizing GEORGI'S wind observations LOEWE [1936 b, pp. 369-370] says: "Even with the lowest temperatures there was at Mid-Ice never a complete calm as in Siberia, but always a sensible wind, making the low temperature very trying . . Of more than 1000 observations at Mid-Ice none showed a calm; only two per cent of all observations gave velocities less than 2-1/2 miles per hour, and only one observation in eight gave a velocity less than 4-1/2 miles. Even with a temperature of nearly - 80°F a wind of 12 miles per hour and a slight amount of driven snow have been experienced." LOEWE therefore concludes that the alleged region of calms and light airs "is nonexistent or, at least, its size in Greenland is very restricted."

The entire concept of a "cold central area" having sharply defined boundaries that remain constant in position because uninfluenced by cyclonic disturbances stands, in LOEWE'S opinion, on questionable ground. To be sure, certain expeditions across Greenland--notably those of NANSEN [1890], KOCH-WEGENER [1930], and RASMUSSEN [1914]--have reported finding a sharply delimited area of that kind, but other expeditions, such as those of DE QUERVAIN [1925], HØYGAARD [MAURSTAD, 1932], and RYMILL [WATKINS, 1932], and LOEWE'S own sledge journeys between West station and Eismitte, have found no definite indications of such an area. "The cyclones that pass over the ice sheet," LOEWE [1935 a, p. 80] reminds us, "are able to disrupt completely the shallow stratum of cold air in the interior region. As a consequence the "cold central area" cannot have any real constancy, either in space or in time. There is, rather, a gradual decrease in temperature toward the interior of the ice sheet (neglecting conditions at its outer borders), the isotherms being spaced approximately like isohypses. It is to be expected, of course, that any sledge journey of sufficient duration will encounter in some part of the interior a spell of clear weather with intense outward radiation and very low temperatures."

Observations by the WEGENER Expedition on the alimentation of the Greenland ice sheet

HOBBS has set up the thesis that large ice sheets differ radically from mountain glaciers, and even from small ice caps, in their mode of alimentation. Whereas mountain glaciers and small ice caps are nourished chiefly by rising air masses whose moisture at the higher levels is condensed into snow, as the result of adiabatic cooling, ice sheets of great extent, HOBBS maintains, are nourished chiefly by descending air currents at the center of a glacial anticyclone, the moisture brought down from the cirrus clouds being sublimated in the form of fine ice spicules and hoar frost as the air is cooled to the point of supersaturation in contact with the intensely cold surface of the ice sheet [HOBBS, 1911, pp. 286-287; 1926, pp. 53-54; 1935, pp. 4-5]. The alleged competence of the glacial anticyclone to supply the ice sheet with sufficient nourishment in this manner to build it up and maintain it in existence in spite of the huge losses which it suffers annually at its margins by melting, evaporation, deflation, and iceberg calving, is, indeed, the kernel of the glacial anticyclone theory. Yet in none of his numerous writings has HOBBS adduced any quantitative data, or even any theoretical considerations, to support his thesis.

The first systematic measurements designed to determine the net quantity of water substance that is added to the higher parts of the Greenland ice sheet in the course of a year were made by the WEGENER Expedition in 1930-1931. They included observations to ascertain the proportionate contributions to the total made by each of the three types of hydrometeors--ice spicules, hoar frost, and snow. As the measurements were made along the 71st parallel, in the middle part of Greenland, the quantities determined are presumably roughly representative of the means for the entire length of the ice sheet, for, as is well known, the climate is wettest in southern Greenland and becomes progressively drier toward the northern end. For all these reasons the data obtained by the WEGENER Expedition have great value, far greater value than those of any other expedition, and deserve special consideration.

As regards the role played in the alimentation of the Greenland ice sheet by ice spicules--"diamond dust" floating down out of a shallow, misty air layer beneath a clear sky--the observations at Eismitte show unmistakably that it is an altogether negligible one. Occurrences of such ice spicules, which because of the beauty of the attendant optical phenomena, sun-bows and parhelia, are not likely to be overlooked, were observed "not more than a dozen times during the year" [LOEWE, 1935 a, p. 90]. They were restricted, naturally, to clear, cold days when truly anticyclonic conditions prevailed. No attempt was made to measure the quantity of water that was brought down in the form of ice spicules on such days. It was no more than a mere "trace."

The reasons for this extreme paucity of moisture precipitated in the form of ice spicules are not far to seek. In the first place, the sublimating air layer directly overlying the surface of the ice sheet has but little depth, a few hundred feet at most, and consequently has small volume. And in the second place, at the low temperatures that prevail on clear days, when outward radiation is least obstructed, temperatures ranging from - 20°C in summer to - 65°C in winter, the air can hold but a very small quantity of water vapor per unit of volume. KURT WEGENER in his supplementary report on Eismitte makes the following comparison with conditions in Germany [K. WEGENER, 1939 a, p. 112]:

"In our latitude a cubic meter of air at a mean temperature of 15°C, and with a relative humidity of 70 per cent, can hold about ten grams of water, but at temperatures such as occur at Eismitte, taking an average of - 31°C, a cubic meter of air, at sea level, can hold only 0.3 gram of water, and at the altitude of Eismitte [3000 meters] only about 0.2 gram. If, therefore, in our latitudes the quantity of moisture produced by sublimation is so trifling that it can be neglected in precipitation totals, the quantity produced in central Greenland, where the vapor content per cubic meter is nearly a hundred times lower, may be ignored altogether."

Yet there is still a third reason for the paucity of spicules which K. WEGENER overlooks. This is the extreme scarcity of nuclei for the crystallization of spicules in the very pure air of central Greenland. Nuclei of some sort, it is now generally admitted by meteorologists [SIMPSON, 1941, p. 120] must be present in order that direct

Table 1--Number of nuclei per cubic centimeter in the air at different types of localities

Locality	Absolute maximum	Absolute minimum	Average
City	4,000,000	3,500	147,000
County (inland)	336,000	180	9,500
Mountain (elev. 2000 m)	27,000	6	950
Ocean	39,800	2	940

sublimation of water vapor shall take place. But in central Greenland, especially on days when anticyclonic conditions prevail, the air is probably as nearly pure and unpolluted as in any place in the Northern Hemisphere. Some conception of the probable lack of polluting substances in it may be formed from Table 1 published by SIMPSON [1941, p. 108].

It may be presumed that in central Greenland, in anticyclonic weather, the nucleus content of the air is of the general order of the minima indicated for high mountains and for ocean, the reasons being: (1) Greenland's isolated position, surrounded by oceans and broad arms of the sea, except at its northwest corner, (2) the great distances from smoke-producing manufacturing centers and large cities, (3) the absence of active volcanoes in Greenland and in the regions that lie to the west of it, across Davis Strait and Baffin Bay, (4) the nearest active volcanoes to windward are in Alaska and on the Aleutian Islands, 2500 to 3500 miles distant, and of those volcanoes none is constantly emitting large quantities of "ash," (5) the active volcanoes in Iceland are only a few hundred miles away, but the "ash" from them is blown prevailingly in easterly directions, and (6) the principal local sources of atmospheric pollution are the periglacial strips of land on the coastal mountains of Greenland. These strips are not covered by vegetation, and from them dust is sometimes blown up on the ice sheet; the bulk, however, is blown away from the ice sheet by the katabatic winds.

As the result of all these circumstances combined, the ice sheet of Greenland is remarkably clean, except immediately along its borders. That dust in noticeable quantities is not blown up on its surface to any considerable distances is evidenced by the fact reported by BROCKAMP [1935, p. 54] that in the walls of a huge crevasse situated at a distance of 62 kilometers from the western margin no dust zones such as commonly mark off the snow deposits of successive years in mountain glaciers could be detected. As a consequence it proved impossible to determine with any certainty the increments of snow which the Greenland ice sheet receives annually at this distance from its border. On the surface of the snow in the immediate vicinity of the crevasse, however, BROCKAMP noticed small colonies of red algae that must have been blown up by westerly winds. And the fact that they could thrive there, it seemed to him, would imply the presence of other wind-transported material, organic or inorganic, but so extremely fine that it was not discernible by the unaided eye.

Needless to add, no dust zones were seen in the shaft four meters in depth which SORGE excavated at a point 200 kilometers from the ice margin, nor in the 15-meter shaft beneath the Eismitte station, which lay 400 kilometers from the margin.

Now, there can be no doubt that the extreme scarcity of nuclei in the air in central Greenland tends to inhibit in some measure the production of ice spicules, and that the air in consequence often remains in a supersaturated state. The fact is definitely indicated by the sudden appearance, with an audible crackling sound, of great swarms of spicules whenever nuclei from an extraneous source are introduced. The nature of the phenomenon--which is familiar to Arctic explorers, but still needs interpretation--will be readily understood from the following excerpt from LOEWE'S account of the desperate sledge journey to Eismitte, in the face of oncoming winter, on which he accompanied ALFRED WEGENER [LOEWE, 1939, p. 175]:

> "The moisture of our breaths at temperatures below - 58°F immediately froze into little crystals, and, as at these low temperatures the air was always supersaturated with water vapor, new crystals then formed all around, just as when a quantity of water cooled below 32°F suddenly congeals into ice crystals if a single crystal of ice is thrown into it. Thus the [sledge] party was continually enveloped by a cloud one-half mile long."

Much more evidence of this sort might be adduced, but the foregoing will suffice, it is believed, to make clear beyond possible doubt that ice spicules sublimed in the shallow layer of supersaturated air immediately overlying the surface of the Greenland ice sheet inherently cannot supply the bulk, or even a substantial part, of the water substance that is required for the nourishment of the ice mass. Nor does it seem probable that these minute hydrometeors can play an important part in the alimentation of the Antarctic ice sheet, for the air temperatures over the crown of that ice sheet are closely comparable to those at the top of the Greenland ice sheet, and the absolute humidity of the air over its surface must be substantially of the same order. In addition, because of the much greater extent of the Antarctic ice sheet and its far greater isolation, the air in its central portion is likely to be even purer than that in central Greenland, and sublimation of ice spicules therefore is probably inhibited even more effectively by reason of the scarcity of nuclei.

Somewhat different in central Greenland is the situation in regard to the role played by hoar frost. The term hoar frost here is used in conformance with SELIGMAN'S definition [1936, p. 49] for the light, feathery ice deposits that are formed upon snow, ice, or other cold substances by direct sublimation of water vapor. It is kept distinct from rime, the proper term for compact, dense ice deposits formed upon cold substances by the freezing of supercooled water droplets. Rime is common in oceanic climates, being formed usually when damp air at temperatures near the freezing point is being orographically lifted; but it cannot occur at the top of the Greenland ice sheet because the temperatures there are far too low. At Eismitte deposits of hoar frost were very frequent, occurring usually at night or in the early morning, when the air directly over the ice sheet was supersaturated with respect to snow or ice. As LOEWE [1935 a, p. 90] has pointed out, the very fact that the production of floating ice spicules is in some measure inhibited by the scarcity of nuclei leaves the air in a condition favorable to the rapid growth of hoar frost upon the snow surface. As a result, even in midsummer "after a spell of clear nights the surface of the ice cap would look like a carpet of moss"[LOEWE, 1936 b, p. 365].

The quantities of water that were contained in such deposits, however, were surprisingly small. Measurements of their water content, it is true, could not be made with regularity the year round, because of frequent adverse weather conditions; but the measurements that were successfully carried out during the more tranquil periods, and especially at times of heavy deposition, nevertheless warrant the belief that the total for the entire year can be no more than a few centimeters. K. WEGENER [1935 a, p. 105] cites some of the maxima recorded. On September 21, 1930, hoar frost accumulated to the thickness of 0.24 millimeters in 24 hours, and in nine days, from the end of May to the beginning of June, 1931, two centimeters of hoar frost were produced. In terms of water it was deposited at a mean rate of 0.18 millimeter per day [ibid, p. 109]. This was one of the periods when the surface of the ice sheet looked like a carpet of moss.

It may be added appropriately that it is now known, chiefly as the result of AHLMANN'S observations in Norway [1929] and OLSSON'S observations in Spitsbergen [1934], that hoar frost deposits do supply a large share of the total annual nourishment of certain glaciers and small ice caps. But it is also entirely clear that such cases are restricted to areas where pronounced maritime conditions and moderate temperatures prevail. As AHLMANN himself has stated [1935, p. 111], in a district having a continental climate, such as central Greenland, hoar frost can hardly play an important role. That fact is unmistakably indicated by the observations at Eismitte.

From the factual evidence adduced, and from theoretical considerations, then, it may properly be concluded that, contrary to HOBBS' contentions, the ice sheet of Greenland is not nourished exclusively, or even in any large measure, by sublimation products from the supersaturated air layer that directly overlies its surface. Ice spicules and hoar frost definitely play only insignificant roles in its alimentation, and there is consequently no reason to suppose that the descending air that replenishes the radially outflowing katabatic winds is the main alimenting agency.

On the other hand, there is abundant and convincing proof that the ice sheet is nourished almost wholly with snow precipitated from maritime air masses whirled up on the Greenland massif. As has already been shown in previous sections, at Eismitte, and by inference on the surrounding parts of the summit plateau of the Greenland ice sheet, in latitude 71°N, snow storms are frequent at all times of the year. GEORGI'S graph sheet, in fact, shows that snow fell at Eismitte on 208 days out of 365--that is, on 57 per cent of all the days in the year. There were about 2000 hours of snow precipitation, LOEWE [1936 b] states, and he adds, to stress the climatological significance of that figure: "The frequency of precipitation [at Eismitte] is therefore not much smaller than at sea level in the highly oceanic climate of northern Norway."

Perhaps even more surprising is the fact that at Eismitte precipitation, taken the year round, is more frequent than at West station, on the western margin of the ice sheet. That station recorded precipitation (snow and rain) on only 130 days out of 365--that is, on only 35.6 per cent of all the days in the year. LOEWE'S tabulation [1935 a, p. 90] shows that the disparity between the frequency at Eismitte and that at West station was greatest in summer and least in winter. The respective percentages are, in winter 50 against 50; in spring 63 against 35; in summer 56 against 21; and in autumn 53 against 33. Surely these figures do not argue for the stabilizing influence of a persistent glacial anticyclone centered over the Greenland ice sheet.

Direct measurement of the quantity of snow precipitated in each storm proved to be impracticable, because of the violent winds that usually accompanied the storms, and also because of the large volume of drifting snow that then filled the air, often to more than man-height. Neither was it possible to determine separately the quantities of snow laid down or removed by the wind at a given place. As for the relatively small quantities of moisture deposited in the form of hoar frost and those lost by evaporation, these could be measured with the requisite accuracy only during periods of fair weather and low wind velocity. Accordingly, it was deemed best to concentrate efforts on determining the net residue of water substance that is added to the ice sheet above the firn line in the course of a year.

To that end, stout bamboo rods were planted at intervals of 20 kilometers along the straight sledge route leading from West station to Eismitte--a total distance of 400 kilometers. Readings of the height of the snow surface at each rod then were made by the sledge parties as they passed. No readings could be made during the winter season, when the weather was too inclement for travel over the ice sheet, but during August, September, and October, 1930, four readings were made on all the rods, except the four highest, which were read only two or three times; and during the spring and summer of 1931 from six to eight more readings were made on the rods, up to the half-way point; above that point, most of the rods were read only three times [WEGENER and LOEWE, 1933, pp. 155-159].

The rod readings, when plotted, give a set of 18 gradually rising and roughly parallel curves showing clearly the progress of firn accumulation at different levels on the western slope of the ice sheet in the course of a year [WEGENER and LOEWE, 1933, p. 163]. Accumulation was most rapid during the winter months, from the beginning of September, 1930, to some time in April, 1931. It was slowest during June and July, and at the lower levels, from the firn line, at an altitude of about 1400 m, to the 60-km point (altitude 1850 m), the curves decline in midsummer as the result of ablation. But even at these lower levels there remained at the end of the 12-month period, August 1, 1930, to July 31, 1931, an appreciable residue of new firn.

From K. WEGENER'S table on p. 164 it appears that the net accumulation of firn in that period ranged from 45 cm at the 25-km point (altitude 1650 m) to 105 cm at the 120-km point (altitude 2150 m). There the zone of maximum accretion began and quantities of 105 to 110 cm predominated as far as the 200-km point (altitude 2500 m). Thence upward over the remaining 200 kilometers to Eismitte the quantities again decreased, but only slightly, the average being 92 cm. From the densities of the firn determined at the different points LOEWE calculates for the entire layer of firn measured on the western slope of the ice sheet a mean water equivalent of 38 cm, or 15.0 inches [LOEWE, 1936 a, p. 325]. The maximum accumulation, at the 140-km point (altitude 2250 m) represents 50 cm, or 19.7 inches of water.

HOBBS questions the value of this method of measuring the net annual accretion of firn at the surface of an ice sheet and enumerates the several factors that must be taken into account, to wit, "precipitated snow (W) plus drift snow (X) plus rime (Y) plus ablation (Z), with due regard to the algebraic sign of each factor" [HOBBS, 1944 a, p. 83]. Yet it is an indisputable fact that the method as employed by the WEGENER Expedition yields at the end of the year precisely the resultant of all those factors. It includes, moreover, certain other factors, which HOBBS does not mention, namely, the effect of the normal shrinking of the firn with age, its loss in depth due to the formation of surficial ice crusts by insolation, and its gains in density and water content from summer rains. In latitude 71°N heavy rains fall occasionally at elevations as high as 6000 feet (1830 m)--that is, 1600 feet (490 m) above the firn line [LOEWE, 1936 b, p. 366]. This rain water does not run off, but sinks into the porous firn, freezes there, and augments its water content.

To a firm believer in the existence of a glacial anticyclone in Greenland the figures cited must seem very large and perhaps based on a period of abnormal conditions, yet there are two reasons for believing that they are fairly representative of average conditions. In the first place, the rod readings along the sledge route, if reckoned from September 1, 1930, to August 31, 1931, yield much larger values of firn accretion than if reckoned from August 1, 1930, to July 31, 1931, the reason being that in 1931 the heavy winter snows set in early in August instead of early in September. K. WEGENER'S table [WEGENER and LOEWE, 1933, p. 164] shows that the readings from September 1, 1930, to August 31, 1931, give measures of firn accretion 20 to 25 cm greater than the readings from August 1, 1930, to July 31, 1931. This implies an additional quantity of six to eight cm, or two to three inches, of water. It may be presumed, therefore, that in some years the mean accumulation may amount to fully 45 cm, or 17.7 inches of water, and the maximum may be as high as 58 cm, or nearly 23 inches.

In the second place the mean accumulation on the western slope, as reported for the 12 months, August 1, 1930, to July 31, 1931 (38 cm, or 15 inches of water), harmonizes very satisfactorily with the mean for the past 20 years which SORGE determined at Eismitte by another method. In the 50-foot shaft which he had dug, SORGE succeeded by means of highly-refined density measurements, which were duly checked by GEORGI and LOEWE, in identifying the successive firn layers deposited from 1911 to 1930. He discovered, to begin with, that at the altitude of Eismitte, where as a rule no melting takes place in summer, the firn consists of alternating hard and soft layers, the harder, denser, and finer-grained layers being winter deposits packed by strong winds, and the somewhat softer, less dense, and coarser-grained layers being summer deposits. Quite unexpectedly, a check on his work was furnished at a depth of 501.5 cm (16.45 ft) by a thin ice crust that must have been produced at the surface by a brief thaw on one exceptionally warm day. It occurred in a layer which, according to SORGE'S density measurements, should be a summer deposit--that of the summer of 1923--and it thus demonstrated the reliability of his method. Search in the Dansk Meteorologisk Aarbog has since revealed that the summer of 1923 was indeed very warm at the coastal stations in Greenland [SORGE, 1935, p. 105].

The mean water content of the series of firn layers identified in the shaft by SORGE proved to be 31.4 cm, or 12.4 inches [SORGE, 1935, p. 117]. This quantity, it is now evident, since the appearance of v. 4, pt. 2 of the reports of the WEGENER Expedition, accords closely with JÜLG'S measurements [1939, p. 340] on the firn in the upper 100-km stretch of the sledge route to Eismitte. The firn there averaged about 92 cm in depth and had a mean density of 0.3393; its mean water content therefore approximated 31.28 cm, or 12.3 inches.

HOBBS contends that the Greenland ice sheet at present is in a starved condition, for lack of sufficient nourishment in the "cold central area." All the snow that falls there, he claims, is blown away by the centrifugal down-slope winds and piled up outside the margins of the ice sheet, where it is "liquidated" in summer. No new layers of firn therefore are being added annually at the top of the ice sheet, and he suggests that the layers measured by SORGE in the shaft at Eismitte may stem from an earlier period when the ice sheet was being steadily built up. "No proof has been supplied," he adds [HOBBS, 1944 a, pp. 95-96], "that they are of recent deposition." As a matter of fact, SORGE'S density measurements supply the very best possible proof that the layers in the shaft comprise an orderly series of annual deposits leading from 1911 right up to the observation year 1930-1931, for their densities decrease upward with a fair degree of regularity all the way from the bottom of the shaft to the surface [SORGE, 1935, pp. 102-138, Figs. 19 and 24]. In addition, the measurements at the rods planted along the sledge route to Eismitte show conclusively that in the course of a year firn to the depth of about one meter accumulates on nearly the entire western slope of the ice sheet, from points about 60 km above the firn line all the way to the top. HOBBS' attempt to discredit the results of SORGE'S painstaking research therefore may well be disregarded.

It is to be noted, finally, that the figures of the WEGENER Expedition for a year's accumulation of firn on the west slope and on the summit plateau of the Greenland ice sheet correspond closely with the figures reported by other expeditions. The fact is all the more significant because the other expeditions used different methods for determining the thickness of annual firn layers and made their observations in different years.

Table 2--Comparison of measurements of firn accumulation by different expeditions

Expedition	Year	Locality	Latitude	Accumulation
			°	cm of water
WEGENER	1930-1931	west slope	71 N	38.0
		summit	71 N	31.4
DE QUERVAIN	1912	west slope	69 N	36.2
		east slope	67 N	33.6
KOCH-WEGENER	1913	west slope	73 N	35.3
		summit	74 N	20.9
		east slope	75 N	15.9

The relatively low figures for the summit and the east slope reported by the KOCH-WEGENER Expedition, it should be explained, are entirely consistent with the progressive diminution in snow precipitation toward the higher latitudes. Together, the tabulated figures afford a general view of the varying rates at which the Greenland ice sheet is actually being alimented in its different parts. The total quantity of water per year which they indicate is truly impressive. LOEWE [1936 a, pp. 317-326], using all the data of this kind that were available in 1936, has calculated that the total net quantity of firn that is added annually to the Greenland ice sheet in the zone above the firn line approximates 425 cubic kilometers, or 101.96 cubic miles, of water. HOBBS' assertion that the ice sheet is in an undernourished state [HOBBS, 1944 a, p. 95], it may be presumed, was made without knowledge of that figure.

It is true, nevertheless, that the losses which the Greenland ice sheet suffers annually in its marginal zone, below the firn line, exceed its annual income, and that its borders are gradually contracting. LOEWE places the total annual losses below the firn line, by ablation and iceberg calving combined, at 445 cubic kilometers, or 106.76 cubic miles, of water. There thus appears to be a deficit in the annual budget of the ice sheet of 20 cubic kilometers, or 4.80 cubic miles of water. But that deficit is very small, considering the total quantities involved, and is caused largely by the wastage and recession of the outlet glaciers. This wastage, in turn, is due, unquestionably, to gradually rising air temperatures near sea level and the rising temperature of the ocean water in the higher latitudes. The deficit in any event is not to be attributed to a recent diminution of snow precipitation at the top of the ice sheet. Any change that might take place there in the annual snow supply would not affect the regimen of the fiord glaciers until after a lapse of several thousand years.

References for Part I

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OUR CHANGING CLIMATE

J. B. Kincer

In a paper published in the Monthly Weather Review in September, 1933, the author discussed long-time temperature trends, and presented data showing that an unusual and extended warm phase of climate had at that time developed through a more or less regular rise in temperature for a comparatively long period of years. The paper also showed that the prevailing condition was widespread, in fact apparently world-wide, and in addition that temperature data up through 1932, the terminal of the records presented in that paper, afforded no indication of an impending trend reversal to more normal thermal conditions in the then near future.

Up to the end of 1945, records for 13 subsequent years have become available, and these are here presented, supplementary to the original data, to determine tendencies since 1932. They show that the general upward temperature trend continued for several years but that the more recent records indicate a leveling off, and even contain currently a suggestion of an impending reversal.

The general temperature tendency since 1932 is illustrated by the following records: At Washington, D. C., 70 per cent of the 156 months, 70 per cent of the winters, 85 per cent of the springs, 100 per cent of the summers, 92 per cent of the falls, and 100 per cent of the years (annual averages) have had above-normal temperature. For Chicago the above-normal percentages have been, for all months 71, winter 77, spring 69, summer 92, fall 85, and for the year 100 per cent. For the entire United States, 67 per cent of the months, 70 per cent of the winters, 54 per cent of the springs, 70 per cent of the summers, and 62 per cent of the falls have had temperatures above normal, while only 23 per cent of the years have had below-normal temperature. The accompanying graphs show that these data are representative of conditions in general.

The reference base "normal" wherever used in this discussion refers to the arithmetic average of all records included in the respective series. Incidentally, it might be mentioned that the normals here employed for these long-record stations usually differ from the standard Weather Bureau normals by only a small fraction of a degree.

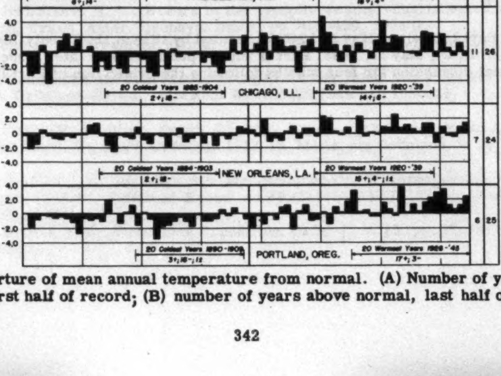


Fig. 1--Departure of mean annual temperature from normal. (A) Number of years above normal, first half of record; (B) number of years above normal, last half of record

Figure 1 shows for five widely-distributed Weather Bureau stations, the year-by-year departures of the mean annual temperature from normal, 1871-1945, the arithmetical mean for the entire period being considered the normal. The stations are Boston, Massachusetts; Philadelphia, Pennsylvania; Chicago, Illinois; New Orleans, Louisiana; and Portland, Oregon. The records for Philadelphia and Portland begin with 1872. A mere glance at this chart shows that the last half of the period for all stations was characterized by a preponderance of positive anomalies and the first half by equally frequent and pronounced negative values.

Dominant features are common to all records, such as for Boston the coldest consecutive 20 years comprised the period 1871-90, with only four above normal and 16 below normal, while the warmest, 1919-38, had 16 above normal and only four below. Each period contains more than 7000 consecutive days, and the temperature for the warmest averaged 2.°3 F per day higher than for the coldest. The first half of the record had only 11 years above normal, while the last half had 26 years above, or more than twice as many.

An examination of the other records discloses, with only minor variations, general conformity with those for Boston. They show from approximately 2.5 to more than four times as many plus anomalies for the last half of the records as for the first half; in all cases the periods comprising the coldest 20 years fall in the first half, with a slight lag for the central and western stations, while the warmest double decade invariably falls in the latter part of the record. The average daily temperature excesses for the warmest periods over the coldest in degrees F are: Philadelphia 2.°0, Chicago 2.°5, New Orleans 1.°6, and Portland 2.°1.

Temperature trends--Long-time weather trends are shown most graphically by smoothing the records; otherwise the year-to-year, or short-period fluctuations tend to obscure any general trend that may be present. Figures 2 to 8 were prepared by a device known as moving summations, or moving averages, where the entry under each date represents the sum, or the average, as the case may be, for the base period indicated up to and including the respective dates of entry. For example, in Figure 2 the first entry under 1855 represents the sum of the mean annual temperatures for the ten years, 1846-55; the second, the sum for 1847-56, and so on through the chart.

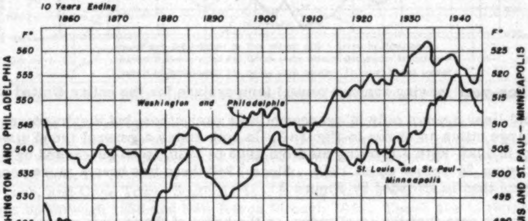


Fig. 2--Ten-year moving mean annual temperature summations, 100 years

Figure 2 shows for 100 years, by ten-year moving summations, the general temperature trends for an eastern and a midwestern area, the former represented by the average annual values for Washington, D. C., and Philadelphia, Pennsylvania, and the latter by similar data for St. Louis, Missouri, and Minneapolis-St. Paul, Minnesota. The general conformity of the trends is apparent, with the coldest decade ending with 1875 or 1876, and the warmest in the late 1930s. The amplitude of the ten-year averages (lowest to highest mean daily temperature for ten years) is 2.°7 for the eastern area and 3.°7 for the western. Up to about 1875 both areas show a temperature recession, and thereafter a general, though irregular, rise for some 60 years. However, the terminals contain a veiled suggestion of a pending recession, but at the same time this may prove to be temporary as shown for the 1900 decade.

It has been suggested that the warm trend, such as here shown, in temperature records for individual stations located in large cities may be more apparent than real because of urban, artificial influences that may be brought about, through expansion and increase in activities, heating, etc., that would influence city-exposed thermometers, but not operative in the nearby open country.

To test this, Figures 3 and 4 were prepared. Figure 3 contains ten-year summation trends for two midwest states, Iowa and Nebraska, in which all Weather Bureau stations within the respective states were included. Most of these records were made in small towns or the open country and only a few in large cities.

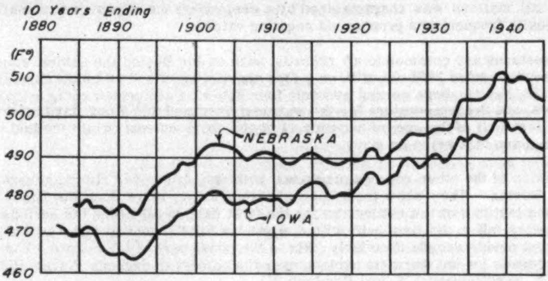
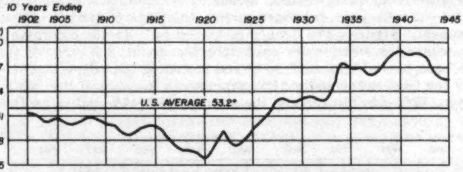


Fig. 3--Ten-year moving average annual temperature summations (state averages)



Total length of record = 636 months. Half of record = 318 months
First half of record; 140 months above normal, 169 below normal, 9 normal
Second half of record; 177 months above normal, 127 below normal, 14 normal

Fig. 4--Ten-year moving average annual temperature for the entire United States

Here the trend lines are not only in agreement with each other, but they conform in general to the records for large cities as shown in Figure 2. In both states a general trend rise began with the decade ending in 1892, with a leveling off from 1903 to 1920, to be succeeded by a pronounced rise for the following 20 years up to 1940. Since 1940 there has been a more pronounced suggestion of recession than is afforded by Figure 2.

It is interesting to note that the amplitudes, on the basis of these state averages, are 3°.7 in both cases, or exactly the same as shown for the St. Louis and St. Paul-Minneapolis trend in Figure 2. That is to say, the temperature for the warmest ten years (approximately 3650 consecutive days) averaged 3°.7 a day higher than for the coldest decade. A remarkable feature of all graphs presented in this paper is the confirmatory evidence they offer through agreement among themselves, often down to small details, as shown for these two states.

To expand further the question of areal limitations on general temperature trends, Figure 4 was prepared. This is based on the average temperature for the entire United States, embodying several thousand records, as determined by areally weighting state averages. Here the current warm temperature phase, on a decade basis, began during the ten years ending with 1921 and extended to 1940. Again we find for the last few years suggestion of an impending recession. This graph covers 53 years or 636 months. For the 318 months comprising the first half 149 had normal or above-normal temperature, while for the last half there were 191 such months. The first half had 169 months below normal and the last half only 127.

In Figure 5 the record of annual temperature for the entire United States, shown in Figure 4, has been broken down into seasons--winter, spring, summer, and fall. It shows that the upward temperature trend has not been confined to any particular period of the year but is common to all seasons. However, the summer advance began first (for the decade ending with 1913) and the other seasons soon fell into line. Here, again, we find in the latter part of the records some indication of a general reversal of trend for all seasons.

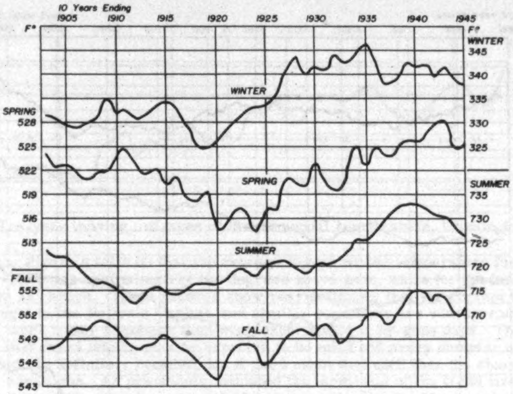


Fig. 5--Ten-year moving summations of seasonal mean temperature for the entire United States, 53 years

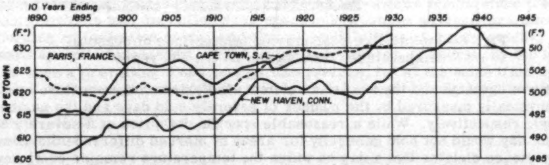


Fig. 6--Ten-year moving summations of annual mean temperature

Weather records for foreign countries have not been readily available for several years, but examination of many of these up to 1930 shows that the current warm phase of climate is more or less world-wide, with the most pronounced upward trend in temperature appearing in middle and higher latitudes of both the Northern and Southern Hemispheres. Figure 6 contains trend graphs for Paris, France, and Cape Town, South Africa, in conjunction with New Haven, Connecticut, the foreign stations up through 1930 and New Haven through 1945. These are in reasonable agreement to the end of available foreign records (1930), after which the New Haven trend continued upward for nine years through 1939, but a subsequent recession is shown in keeping with the preceding graphs.

Outstanding features of recent Washington weather--A more detailed examination of weather records for Washington, D. C., discloses that the current warm climatic phase here has very definitely brought about pronouncedly milder winters and much hotter summers than were experienced some half century or so ago. For example, for the last 25 years, on an annual basis, 1921-45, 22 have been warmer than normal, while for a similar period from 1855 to 1879 only three had above normal warmth. Twenty-five years have approximately 9000 consecutive days, and for the warmer period the temperature averaged 2° a day higher than for the colder. Again, during the last 25 years 20 winters, 18 springs, 20 summers, and 22 falls have had excesses in temperature, against 7, 6, 10, and 11, respectively, for the 1855-79 quarter of a century.

Figure 7 shows the general seasonal temperature trend in Washington for the last 129 years. For the fall season the genesis of the current warm phase covered the quarter-century ending with 1880; for spring that ending with 1892; for winter about 1920; and for summer about 1927. It must be remembered that to instigate a rise in the trend curves representing 25-year moving temperature summations, the 25-year period immediately preceding the date of incipient curve change must be warmer than the immediately preceding similar period. So, even in this apparently rather recent summer elevation in the curve, the summation producing the change included all records back to 1902, or more than 40 years ago.

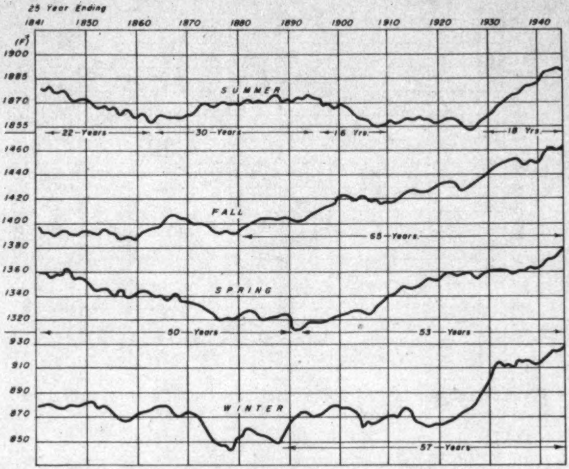


Fig. 7--Twenty-five year moving summations of seasonal temperature, Washington, D. C., 129 years

The severity of a winter and the heat of a summer, the extreme temperature seasons of a year, may be physically measured by the number of severely cold days and the number of extremely hot days, respectively. While a reasonable specific definition of a severely cold day and an extremely hot day would not hold generally for areas of marked differences in climate, in Washington experience dictates that a day on which the temperature remains continuously below freezing is considered by the man in the street as a severely cold day, and one on which the temperature rises to 90° or higher as an outstandingly hot one. We have considered that the number of such respective days affords a reasonable yardstick to measure the abnormalities of the respective seasons and for comparing one year with another.

Figure 8 indicates the general trends of the number of such days (both cold and hot) in Washington for the 74 years, 1871-1945. It shows that the average number of cold winter days for the 20 winters, 1871-1890, was 17 per year, while the average for the last 20 years has been only 11. The trend to hotter summers has even been more pronounced than to milder winters. In this case we find for the 20 years, 1888-1907, that the average number of hot days per year was only 19, while for the last 20 years, up to 1945, the average has been 34 per year. So during the last 20 years in Washington there has been an average of nearly twice as many hot days per year as there were in a similar period some 40 years ago.

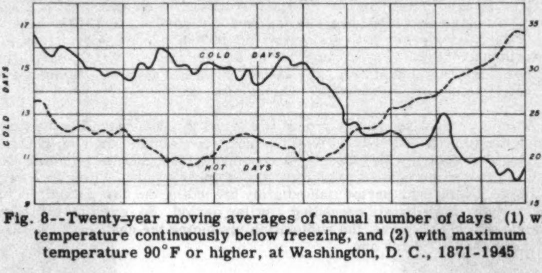


Fig. 8--Twenty-year moving averages of annual number of days (1) with temperature continuously below freezing, and (2) with maximum temperature 90°F or higher, at Washington, D. C., 1871-1945

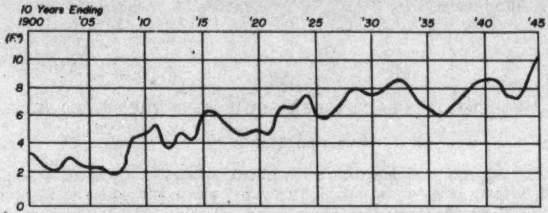


Fig. 9--Ten-year moving averages of lowest annual temperature, Washington, D. C.

Furthermore, Figure 9 tells us that the average lowest winter temperature for Washington for the decade 1898-1907 was approximately two degrees above zero, while for the last ten years the average has been 11° above. These records show very definitely that the current warm phase of climate has brought to the Nation's Capital, and similar conditions are widespread, decidedly milder winters and much hotter summers than were experienced in by-gone days. This does not connote, of course, that every winter may be expected to be mild and every summer hot until the temperature trend has definitely receded, but it does mean that until then the chances are largely in favor of such conditions. As previously indicated the terminals of the trend lines here presented do offer a suggestion of the eve of a reversal of trend, but the length of that part of the records offering such suggestion is yet too short to predict with confidence.

Temperature trends and long-range weather forecasting--While temperature trends as here developed do not provide a tool for definite and specific long-range weather forecasts, they are valuable in affording an indication of expectancies or probabilities of future weather beyond the range of standard synoptic forecasting. Limitations are imposed, of course, by the lack of advance knowledge as to when a prevailing trend may go into reverse, but at the same time the fact is definitely established that once prevalent these trends are of comparatively long tenure.

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REGIONAL CONTRASTS IN HOT DEGREE-DAY UNITS IN THE UNITED STATES

Stephen S. Visher

At the Annual Meeting for 1945, a paper was presented on degree-day units, especially on the regional contrasts in their range or variation. That paper was published in the Transactions for August, 1945 (v. 26, pp. 45-48).

The term "degree-day," invented by a heating engineer and adopted by the United States Weather Bureau, has been applied hitherto to the sums below 65°F, for which the term "cold degree-day units" is here proposed. The sums of the temperatures above 70°F, calculated in the same way as cold degree-day units, is the subject of this paper. A day having a daily mean temperature of 71° has one hot degree-day unit; a day with a mean of 85° has 15 units. Twenty days with means of 85° have a total of 300 units. The annual average number of hot degree-day units in the United States has been laboriously calculated from "Daily Normal Temperatures in the United States," Supplement 25 of the Monthly Weather Review, published in 1925.

Figure 1 reveals that the northern and western borders of the country and the western mountains and lofty plateaus generally lack hot degree-day units. By contrast, much of the southern part of the country has more than 1000 units while the southern parts of Florida and Texas have more than 2000 such units. There is a sharp southward increase in these units in most of the eastern half of the country. For example, Philadelphia has nearly twice as many as New York; Washington, a fourth more than Philadelphia; Atlanta, more than twice as many as Washington. Similarly, Cincinnati has nearly four times as many such units as Detroit; St. Louis, about twice as many as Cincinnati; and Memphis, nearly twice as many as St. Louis. The cities on the Pacific Coast, except Los Angeles, have none. Los Angeles, where the Weather Bureau station is some 20 miles inland, has 45 units a year, practically the same number as Erie, Pennsylvania.

Daily normals above 70° are limited to the summer months in most of the north. The southern states, however, have many days in spring and fall that have normals above 70°. Figure 2 shows the number of hot degree-units occurring from September 1 to May 31. It reveals that the southern parts of Texas and Louisiana and most of Florida have more than 500 hot degree-day units in spring and fall. Key West has 1463. Southwestern Arizona and the nearby part of California also have more than 500 units, Yuma having 730.

The number of days per year having daily normals above 70° are shown on Figure 3. It reveals that no days are this warm along the northern border of the country or on most of the Pacific Coast. By contrast, about 100 days are this warm approximately half way between Canada and the Gulf of Mexico, while near the Gulf about 200 days have normals above 70°; southern Florida has more than 300 such days. This original map is based on the data given in Supplement 25, referred to above.

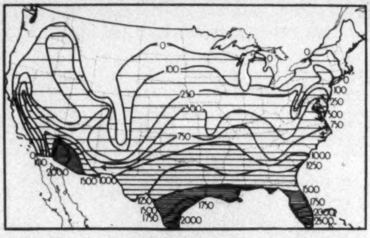

Fig. 2--Average annual hot degree-day units during spring and fall

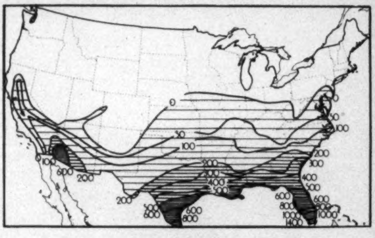

Fig. 1--Average annual number of hot degree-day units

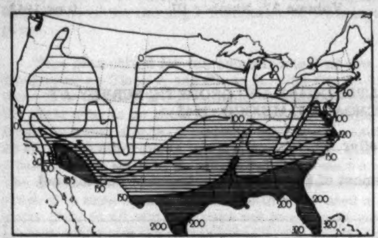

Fig. 3--Average number of days per year with daily normals above 70°F

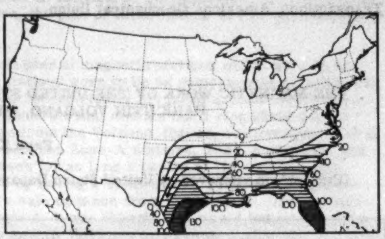

Fig. 4--Average number of nights per year with minimum temperatures above 70°F

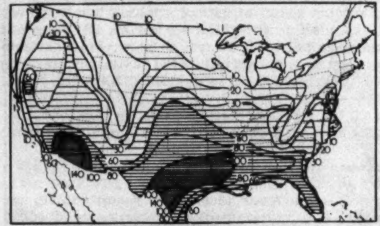

Fig. 5--Average number of days per year in which the maximum temperature reaches or exceeds 90°F

Figure 4 shows the average number of nights in which the temperature does not fall below 70° It supplements Figures 1-3 though it is based on data in the official "Average Daily Minimum Temperatures, 1916-1935," mimeographed, November, 1944. It reveals that along the Gulf of Mexico there are about 80 such "enervating" nights per average year, while in southern Florida there are more than 100 (111 for the average of the section, to be precise). In a part of southeastern Texas there are normally 135 such hot nights per year.

The final map of this series (Fig. 5) is likewise based on recent data, and shows the average number of days per year in which the maximum temperature reaches or exceeds 90°. It reveals that nearly one-fifth of the country has fewer than ten such days, while another fifth has more than 60, and sizeable areas in the south and southwest have more than 100, and small areas there over 140. Yuma normally has 164 days with maxima above 90°, and 96 days with maxima of 100° or higher. Figure 5 is based on the records for many regular Weather Bureau stations as presented in the local official summaries to 1944, supplemented by deductions from the "Average Daily Maximum Temperatures, 1916-1935."

These maps, based on official data, reveal sharp regional contrasts in the intensity and duration of high temperatures, and in the need for artificial house cooling, "air conditioning," if maximum comfort and intellectual activity are to be attained. With the spread of industrialization, increased efficiency of air conditioning apparatus, and higher living standards, information as to the amount of high temperature in each part of the country becomes of increasing interest. Hence, this paper, despite its introductory character, affords interest.

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THE MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY AT PARÍCUTIN VOLCANO, MICHOACAN, MEXICO, 1945

Fred Keller, Jr.

(Publication approved by United States Department of State and Department of Commerce)

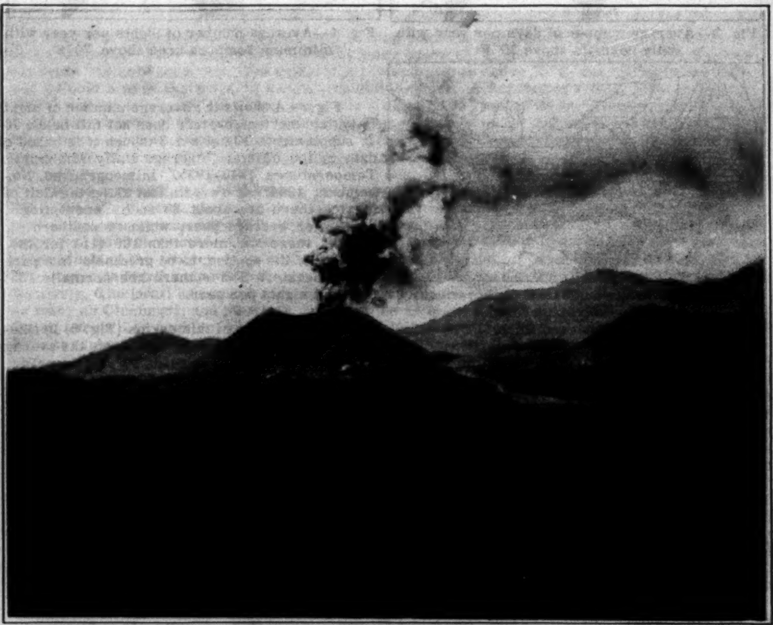

Fig. 1--Parícutin Volcano with church tower and Magnetic Observatory in foreground

Object of investigation--A study of the Earth's magnetic field in the vicinity of Parícutin Volcano (see Fig. 1), in the State of Michoacan, Mexico, was made by the United States Coast and Geodetic Survey in cooperation with the United States Department of State and the Mexican Government from January to August 1945. (This is one of a number of scientific and cultural projects undertaken abroad by the United States Government under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation, Department of State.) The object of this investigation was to ascertain if changes occur in the Earth's magnetic field associated with the development of a volcano. The changes looked for were defined as those of deep-seated origin and not those caused by the cooling of the surface lava flows [McNISH, 1944; see "References" at end of paper].

Plan for magnetic work--At a conference on December 20, 1944, attended by O. W. SWAINSON, H. E. McCOMB, H. A. COTTON, H. H. HOWE, and R. E. GEBHARDT of the Coast and Geodetic

Survey, and H. F. JOHNSTON, E. H. VESTINE, and A. G. McNISH of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the plan of investigation at Parícutin was proposed.

This plan called for the establishment of two classes of magnetic stations which were to be designated as Class A and Class B. The Class-B stations were to be as numerous as possible and were to be located in conveniently accessible places concentrically arranged around the Volcano--the inner ring to be about 1.5 km, the second ring about 3.0 km, and the third ring about 4.5 km from the cone. Class-A stations were to be remote from the Volcano, that is, at distances of 10 to 20 km. The differences in vertical intensity (ΔZ) between Zone-A stations, Zone-B stations, and a base station were to be measured about once a week for as long a period of time as feasible. The diurnal variation correction was to be secured by having a continuously recording magnetograph at a base station which was to be located at a safe distance from the Volcano. If the differences (ΔZ) at all stations were not found to be constant, it was thought this would indicate that important changes were taking place in the Earth's magnetic field due to volcanic action.

Field personnel--Geophysicist AUSTIN E. JONES was sent to Parícutin as a Chief of Party for the Coast and Geodetic Survey to carry out the program which had been planned at the conferences. He started the field work on February 18, 1945, after conferring with officials of the Mexican Government in Mexico City, and made magnetic measurements until the close of the program on August 25, 1945. During the first two months and later in July he was assisted by Geophysicist FRED KELLER, Jr., of the Survey.

Excellent cooperation was received from the officials of the Mexican Government and from all the scientific personnel representing the many organizations interested in the study of Parícutin.

Cost of survey--An examination of the accounts of the Chief of Party shows that the total cost of the work was approximately \$6800. This is a little less than \$1000 per month. The total sum was divided among the several items of major expense as follows: Salaries, \$3734.70; per diem, \$2014.50; construction of Observatory, \$144.84; miscellaneous, \$876.63; total \$6770.67. The cost of constructing the Observatory was low, because the major portion of the building was obtained from an abandoned one, and because the cost of labor was approximately \$1 per man day. The miscellaneous item includes all expenses of trucking and commercial traveling of the geophysicists working on the problem.

Previous work--A relationship between magnetic variation and the occurrence of an earthquake or volcanic eruption is said to exist by Y. KATO [1934, 1935]. He has reported that a magnetic disturbance appears shortly before an earthquake or volcanic eruption, while after the earthquake or eruption the magnetic field appears to recover. It seems reasonable that changes of magnetic field should result from crustal movements or changes during an earthquake; however, the occurrence of a magnetic disturbance several months before a volcanic eruption may be coincidental. Reports of magnetic disturbances associated with volcanic eruptions, such as Krakatoa in 1883, indicated that the disturbance followed the geologic action.

In 1941, A. G. McNISH [1941] reported that magnetic profiles across a volcanic rift in Guatemala showed low and erratic values of vertical intensity; however, the masking effect of surface rocks on magnetic anomalies made inferences about disposition of subsurface structures hazardous.

The eruption of Parícutin Volcano in Mexico started on February 20, 1943. R. R. BODLE and N. C. STEENLAND [1944] of the United States Coast and Geodetic Survey made a magnetic survey of the area during May, June, and July, 1943. They established an excellent network of stations which covered about 25 square miles around the Volcano. The results of this survey have been published with the data given in tabular form and the correlation with the Volcano indicated by index figures, each of which shows that the magnetic vertical intensity lies within a certain range. However, it is felt that data such as presented in their report can be more strongly shown by plotting the isogams of vertical intensity over the known geography. This has been done (Fig. 2), and it shows that the Volcano is associated with a definite curvature or structure of the Earth's magnetic field. The Parícutin cone is located on the nose of a magnetic high which has an axis trending northeast-southwest. Flanking the cone on its northern and southeastern sides, there is a low, the shape of which roughly parallels the route taken by the lava flows. Apparently the magnetic field follows the general topography with a tendency for the higher vertical-intensity values to be over the higher land. This is to be expected, since the area is made up of hills which are old lava flows and all the underlying rocks in the area are basic lavas. Generally rock structures which are slightly magnetic are polarized with the south poles in their higher parts in the Northern Hemisphere. This appears to be the case here and any anomalies that may be due to the Volcano would be masked by the heterogeneous data obtained over old lava flows.

Field procedure

Magnetic instruments--The instruments used for the magnetic work in 1945 included one Askania vertical-intensity field-balance, one continuously recording magnetograph using a modified Askania as a Z-variometer, one United States Coast and Geodetic Survey absolute magnetometer, one earth inductor loaned by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, one Helmholtz coil for calibrating the Askanias, three marine chronometers, two communications radio receivers for getting time signals, and all the necessary equipment for operating a magnetic observatory and conducting a field survey.

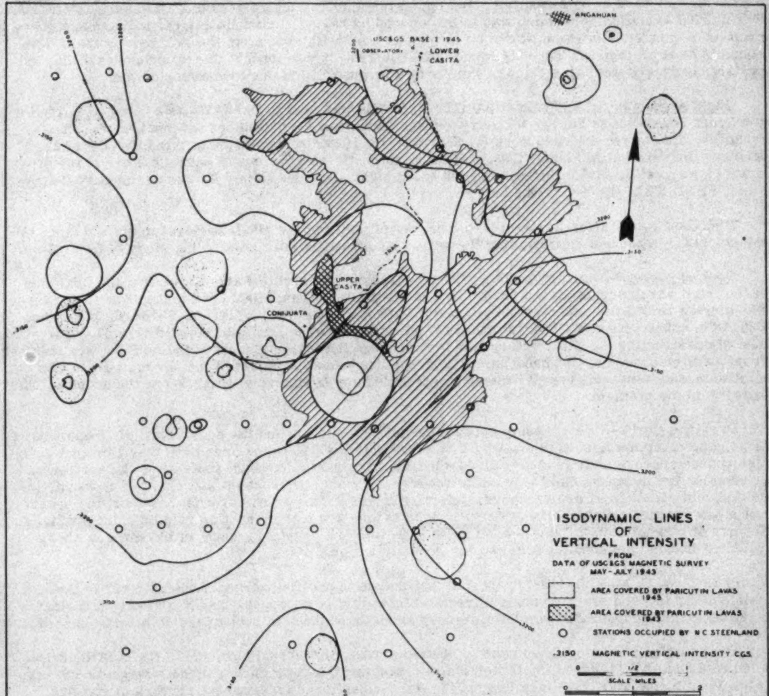
ANGAHUAN
USC&GS BASE I 1945
OBSERVATORY
LOWER CASITA
UPPER CASITA
CONIJUATA
.3200
.3150
ISODYNAMIC LINES OF VERTICAL INTENSITY
FROM DATA OF USC&GS MAGNETIC SURVEY MAY-JULY 1943
AREA COVERED BY PARICUTIN LAVAS 1945
AREA COVERED BY PARICUTIN LAVAS 1943
STATIONS OCCUPIED BY N C STEENLAND
.3150 MAGNETIC VERTICAL INTENSITY CGS
0
1/2
1
SCALE MILES
0
1
2
SCALE KM

Fig. 2--Isodynamic lines of vertical intensity, 1943

The Askania field balance used for measuring the station differences was the same instrument which was used by STEENLAND for a survey of the Parícutin area in 1943. Shortly after this work, the temperature coefficient was determined to be -2.7 gammas per degree C ($-2.7\gamma/^\circ C$) for a vertical-intensity field equivalent to that at Parícutin [BODLE and STEENLAND, 1944]. This value was also used for the work in 1945. Erratic readings and poor closures for many of the traverses at first suggested that the knife edge of the Askania had been chipped during the season of 1945; however, a careful examination with a microscope revealed that the knife edges were in good condition. The counterweights, magnet blades, and releasing device were also found to be in good condition at the close of the survey. Therefore, it is probable that the erratic readings were caused by fine volcanic ash which infiltrated the protecting cases. The scale value was determined frequently and it remained reasonably consistent during the five-month period of observations. The scale values determined in the field are given in Table 1.

Table 1--Scale values, Askania balance, Parícutin, 1945

Date	Observed scale value	Difference from mean
1945	γ/sc.-div.	pct
Feb. 23	13.4	0.0
Mar. 7	13.1	2.2
June 13	13.1	2.2
Aug. 10	13.6	1.5
Aug. 24	13.7	2.2
Mean	13.4	1.6

During the last part of the observing program, JONES made numerous readings of the Askania at each station and computed the average deviation from the mean for the individual readings. He found that the average deviation was 0.26 scale division or 3.5 gammas. This may be considered to be the reliability of the individual readings.

Prior to the Parícutin work the continuously recording magnetograph was set up and tested at the Cheltenham Observatory of the Coast and Geodetic Survey. The magnetograph consisted of a clock-driven recorder and modified Askania vertical-intensity field-balance used as a Z-variometer. The Askania was loaned to the Coast and Geodetic Survey by the Gulf Research and Development Company. It was mounted on a dip circle base and the telescope was replaced with a prism. The temperature poise was set at a point which gave temperature compensation for a vertical intensity field equivalent to that expected at Parícutin. This was done in the laboratory at Cheltenham by reducing the vertical field at the center of the recording magnet to 31,900 gammas with a battery of control magnets immersed in ice. The temperature poise was finally locked in a position that gave a temperature coefficient of $-0.2\gamma/^\circ C$ for the latitude of Parícutin. When the instrument was set up on the pier at the San Juan Base Station in Mexico (Fig. 3), it was not necessary to readjust the poise, since the recording spot was "on scale." Frequent determinations of the scale value of the Z-variometer indicate that the instrument held its calibration throughout the field program. The scale values determined in the field were as in Table 2.

Table 2--Scale values, Z-variometer, determined at San Juan Base Station

Date	Observed scale value	Difference from mean
1945	γ/mm	pct
Mar. 12	2.66	3.3
June 12	2.77	0.7
July 30	2.73	0.7
Aug. 20	2.76	0.4
Aug. 24	2.81	2.2
Average	2.75	1.5

The constant of the Helmholtz coil was checked by comparing scale values determined for the Gulf Askania with both the coil and the standard scale-value magnet used at the Cheltenham Observatory. The scale value determined with the magnet was 3.50 γ/mm and with the coil 3.41 γ/mm.

The absolute instruments, magnetometer 38 and C. I. W. earth inductor 171, were used to determine D, H, and I at the Uruapan Base Station and at the San Juan Base Station. These instruments were standardized at the Cheltenham Observatory before and after the season of 1945. The preliminary index corrections that have been applied to the data obtained with these instruments are: D, $-0'.5$ east; I, $-0'.5$ north; H, -12γ. During the dry season in February, March, and April, it was found that the combination of vibration from the Volcano and deflections from atmospheric static caused the galvanometer to behave so erratically that it was not possible to make precise determinations of the dip at the San Juan Base Station.

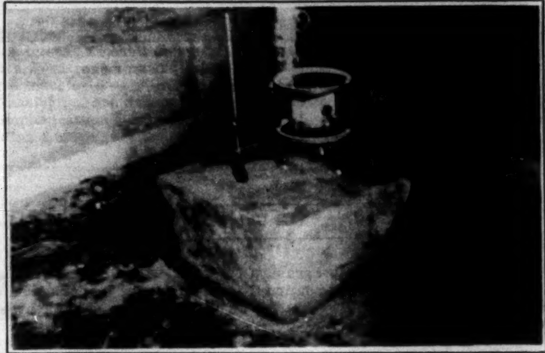

Fig. 3--Modified Askania on pier in Observatory at San Juan Base

Seismic instruments--In conjunction with the magnetic work, seismographs were operated in an attempt to secure an activity index for possible correlation with the magnetic data. Two Coast and Geodetic Survey vibration meters (Fig. 4), one Neumann-LaBarre vibration meter, and two recorders were taken to Mexico. The Coast Survey vibration meters were operated intermittently in the same building as the magnetograph. The Neumann-LaBarre was to be set up at some distant locality, such as Morelia; however, this was not found to be feasible.

Miscellaneous instrumental equipment--Lamps for the seismograph and the magnetograph were operated from storage batteries. The batteries were charged about every two days with a gasoline-driven charger. One chronometer was used to make marks every minute on the seismic records and one was used to make the absolute observations and to carry time corrections from the radio to the chronometer of the seismograph. The third chronometer was damaged in transit from Uruapan to the Volcano and was not used after the first few days.

Radio reception in the immediate vicinity of the Volcano was poor; however, after a 50-foot antenna was installed at the Base Camp, time signals from WWV in Washington, D. C., could usually be received during the evening hours.

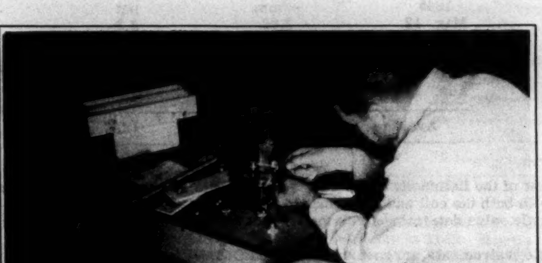

Fig. 4--Assembling the Coast and Geodetic Survey vibration meter

San Juan Base Station--The San Juan Base Station (Figs. 5, 6, and 7) was established in an ash-covered field about five km north of Parícutin Volcano and 180 meters northwest of the Base Camp constructed by the Committee for the Study of Parícutin. It is 180 meters north of the road from Angahuan to Los Reyes in line with the church tower of destroyed San Juan de Parangaricutiro and the center of Parícutin cone. The field in which the station is located is bounded by a barranca (gully) 45 meters to the west, by a low forested hill 75 meters to the east, and by the north side of the San Juan flow 320 meters to the south of the station which is 29.6 meters north of the north side of the Observatory building. The station is marked with a concrete post which is approximately 30 cm in diameter and 75 cm long, buried so that its top is flush with the ash. The exact point is indicated by a copper nail embedded in the center of the concrete marker (see Fig. 7).

Four auxiliary stations were established to ascertain whether or not the area had a low magnetic gradient. These are shown on the sketch but probably cannot be recovered, since they were marked with wooden stakes only. The true azimuths (reckoned from south around by west from 0° to 360°) and distances to these auxiliary stations from the Base Station are as in Table 3.

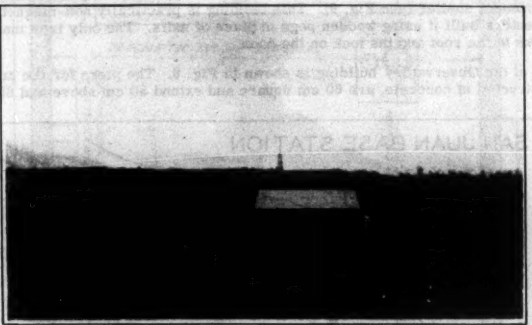

Fig. 5--San Juan Base Station in line with Observatory, church tower, and Volcano, looking south

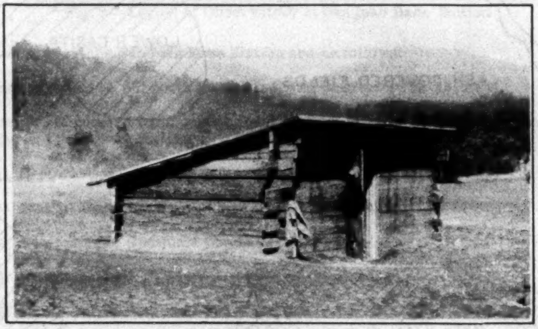

Fig. 6--Observatory building at San Juan Base Station, looking northeast

Table 3--Azimuths and distances to auxiliary stations

Station	Azimuth	Distance
		meter
II	71° 42′.8	34.7
III	28 51.1	97.1
IV	342 01.3	100.6
V	251 48.2	44.4

The Observatory building was located so that the Z-variometer would be approximately 30 meters south of the Base Station. Actually, it is 29.6 meters from the north side of the building to the Base Station. The building was constructed by disassembling the abandoned jail in San Juan de Parangaricutiro and reassembling it at the Base Station. It was only necessary to install a roof, build a light trap, and seal the walls with a mixture of plaster and glue to have a substantial light-tight instrument shelter (see Fig. 6). This building is practically non-magnetic, since the Tarascan carpenters built it using wooden pegs in place of nails. The only iron materials used were a few tacks in the roof and the lock on the door.

The layout of the Observatory building is shown in Fig. 8. The piers for the magnetograph, which are constructed of concrete, are 60 cm square and extend 30 cm above and 60 cm below the

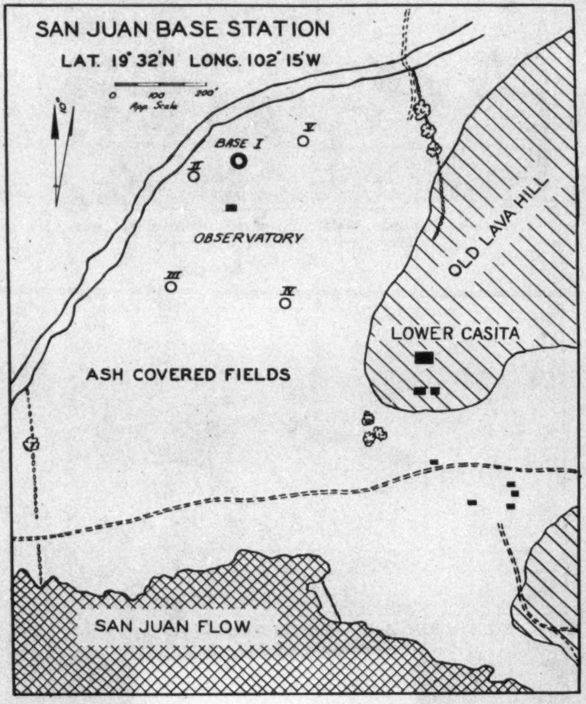
SAN JUAN BASE STATION
LAT. 19° 32′N LONG. 102° 15′W
0
100
200′
App. Scale
BASE I
II
V
OBSERVATORY
III
IV
OLD LAVA HILL
LOWER CASITA
ASH COVERED FIELDS
SAN JUAN FLOW

Fig. 7--Sketch of San Juan Base Station

ground. They are approximately two meters from center to center. The magnetic meridian and prime vertical are marked on the north-south and east-west walls with copper nails. The T-shaped pier for the seismograph extends 60 centimeters below and 10 cm above the ground. It is roughly one meter long and one-half meter wide, with the T-end made to fit a Jaggar recorder. Forty-five cm of volcanic ash were removed from the floor inside the building, so the floor is hard yellow clay which is relatively free from dust. It was necessary to "ditch" the building during the rainy season to keep the heavy runoff from entering.

The magnetograph was operated about 90 per cent of the time from March 11 to August 23. Absolute determinations of D, H, and I were made at the Base Station on March 14, 16, and 20, 1945, and repeated on June 11, 1945. The Askania field-balance was checked at the Base Station before and after each traverse. The diurnal-variation data were supplied by the magnetograph.

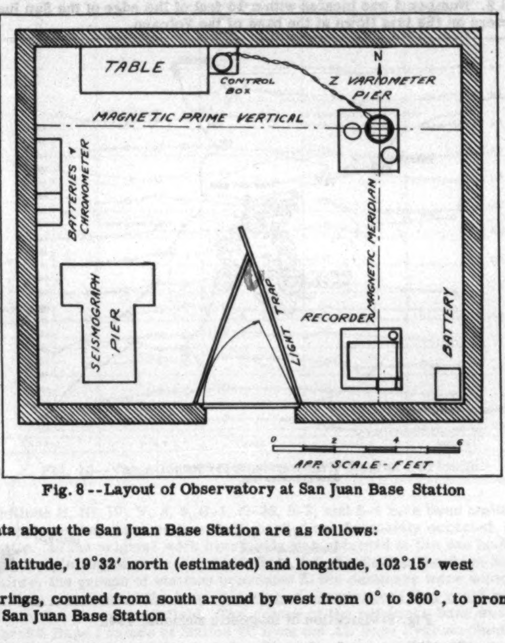

Fig. 8 --Layout of Observatory at San Juan Base Station

Pertinent data about the San Juan Base Station are as follows:

Position, latitude, 19°32′ north (estimated) and longitude, 102°15′ west

True bearings, counted from south around by west from 0° to 360°, to prominent objects from the San Juan Base Station

(1) Centerline of upper window and spike of San Juan church tower	5°50′.6
(2) Flag at Upper Casita	5 40 .5
(3) Centerline of Conijuata Casita	17 50 .3
(4) Tancitaro Peak	25 09 .0
(5) Hump on Tancitaro to west of peak	26 07 .6
(6) Triangulation Cross on hill beyond lava	343 30 .2

Approximate azimuths to Parícutin cone as determined on March 19, 1945

East rim of Parícutin crater	3°37′
West rim of Parícutin crater	6 58

Location of stations--The locations of all the stations occupied by JONES during the 1945 season are shown on the sketch in Figure 9. The rings proposed by the committee for location of these stations have been drawn to show how the distribution agrees with the original plan. Those stations marked S are approximate reoccupations of points previously occupied by STEENLAND in 1943.

All of the points were marked with wooden pegs set in the center of a triangle formed by three tripod pegs. This enabled the observer to occupy the same point within an inch of the previous occupation. The San Juan Base and Uruapan Base were marked with concrete monuments. The Uruapan Base was established by STEENLAND in 1943 as a regular magnetic repeat station.

In the proposed plan of the survey it was stated that the proximity of stations to recent lava flows should not be less than 200 meters. This procedure was followed with all stations except numbers 4, 8, and 9. Number 4 was located within 15 feet of the edge of the San Juan Flow, and numbers 8 and 9 were on the lava flows at the base of the Volcano.

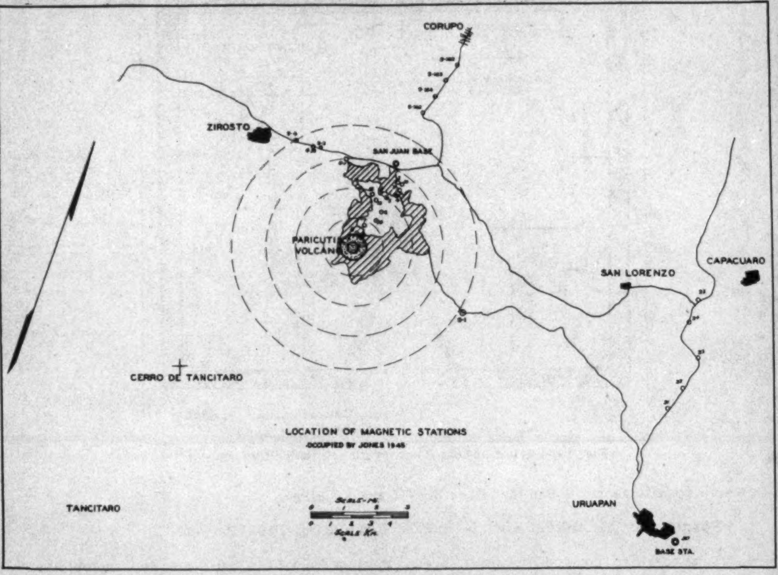

Fig. 9--Location of magnetic stations, 1945

Field procedure--The differences in magnetic vertical intensity between the San Juan Base Station and Stations 1 to 7 were measured once per week from March 7 to August 24. As the other stations were established, they were occupied as frequently as possible.

The diurnal-variation and base-drift corrections were obtained by repeating observations at the Base Station before and after each traverse and by scaling the diurnal variation from the records of the magnetograph.

Absolute determinations were made at the San Juan Base and at the Uruapan Base twice during the program.

Results

The results obtained by measuring the differences in magnetic vertical intensity from an assumed constant base, for Stations 20-25, S-162 to S-165, and Base 1-14 are shown graphically

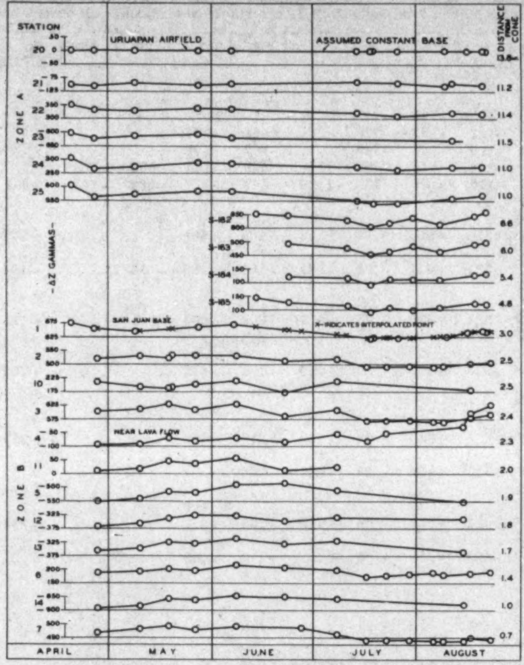

Fig. 10--Variation of vertical-intensity field at Paricutin

in Figure 10. Stations II, III, IV, V, 8, 9, G-1, G-36, S-3, and S-4 have been omitted from the summary sheet, because they were neither well marked nor frequently occupied, and the values tended to be erratic. In the original work everything was referred to the San Juan Base Station; however, preliminary plotting of the results indicated that the field at the Base Station was not constant. Therefore, the groups of stations presented in the summary were selected to show the results, because they represented the longest series of observations that could be referred to the Uruapan Base 20, on the Uruapan Airfield. The change of the reference base was accomplished by subtracting the ΔZ Base I values of Station 20 from the ΔZ Base I values obtained for the other stations. On the days when Base 20 was not observed, the amount to be subtracted was interpolated between the nearest observed values. The ΔZ Base 20 values were then plotted to show the variation of each station with time. The reliability of each point is thought to be about plus or minus ten gammas.

It will be noted that the variations of the ΔZ values for Stations 21, 22, 23, and 24 are much less than the variation for the other stations which are closer to the Volcano. A straight line may be fitted to the points for Station 21 so that the deviation of any value from the line will not be more than ten gammas. This line will be parallel to the assumed constant base line for station 20. Straight lines may also be fitted to the values for Stations 22, 23, 24, and 25 with average deviations of individual points less than ten gammas; however, these lines will diverge from the parallelism noted between the lines for Stations 20 and 21. This may indicate that there is a slight warping of the field about 11 miles east of the Volcano.

Table 4--Relative values of vertical intensity at principal stations near Parícutin Volcano
(Values from March 7 through April 17 are referred to Base 1, all others to Base 20)

Date	Base 1	2	3	4	5	6	7	8[b]	9[b]	10	11	12
1945												
Mar. 7	0	....	....	....	....	....	....	....	....	....	....	....
13	0	-122	- 36	....	....	....	....	....	....	....	....	....
21	0	-121	- 32	-736	....	-461	-171	....	....	....	....	....
Apr. 4	0	-129	- 48	-749	....	-462	-178	....	....	....	....	....
12	0	-134	- 45	-758	-1184	-449	-165	-680	-764	....	....	....
17	0	-116	- 38	-739	-1189	-447	-177	-682	-793	-469	-616	-1006
19	+676	....	....	....	....	....	....	....	....	....	....	....
26	+655	....	....	....	....	....	....	....	....	....	....	....
27	+654[a]	+520	+603	- 92	-552	+188	+468	....	....	+212	+ 11	-368
May 7,8	+646	....	....	....	....	....	....	....	....	....	....	....
9	+647[a]	+531	+611	- 91	-541	+191	+480	- 54	....	+194	+ 18	-356
10	+648	....	....	....	....	....	....	....	....	....	....	....
17	+653	....	....	....	....	....	....	....	....	....	....	....
18	+654[a]	+524	+630	- 70	-514	+202	+492	-145	....	+188	+ 46	-339
19	+655[a]	+533	....	....	....	....	....	....	....	+191	....	....
24	+659	....	....	....	....	....	....	....	....	....	....	....
26	+660[a]	+533	+609	- 80	-519	+196	+478	....	....	+202	+ 37	-325
27	+661	....	....	....	....	....	....	....	....	....	....	....
29	+663[a]	....	....	....	....	....	....	....	....	....	....	....
June 6	+671	....	....	....	....	....	....	....	....	....	....	....
7	+670[a]	+532	+630	- 68	-489	+216	+492	....	....	+215	+ 57	-328
13	+663[a]	....	....	....	....	....	....	....	....	....	....	....
22	+653[a]	+513	+586	- 84	-484	+206	....	....	....	+173	+ 13	-348
23	+652[a]	....	....	....	....	....	....	....	....	....	....	....
27[d]	+648[a]	....	....	....	....	....	+486	- 5	....	....	....	....
July 7	+636[a]	+521	+609	- 54	-510	+198	+461	....	108	+214	+ 24	-334
10	+633[a]	....	....	....	....	....	....	....	....	....	....	....
16	+626[a]	+492	+568	- 78	....	+174	+439	....	....	....	....	....
17	+617	....	....	....	....	....	....	....	....	....	....	....
18[e]	+623	....	....	....	....	....	....	....	....	....	....	....
21	+624[a]	...	....	....	....	....	....	....	....	....	....	....
22	+624[a]	+492	+570	- 52	....	+178	+440	....	....	....	....	....
23	+624[a]	....	....	....	....	....	....	....	....	....	....	....
25-26	+622	....	....	....	....	....	....	....	....	....	....	....
29	+625[a]	+493	+571	....	....	+183	+441	+ 4	....	....	....	....
30	+625[a]	....	....	....	....	....	....	....	....	....	....	....
Aug. 5	+627[a]	+490	+565	....	....	+189	+437	- 19	191	....	....	....
7	+628[a]	....	....	....	....	....	....	....	....	....	....	....
8[f]	+627	+494	+565	....	....	+179	+437	- 19	-201	....	....	....
10	+632	....	....	....	....	....	....	....	....	....	....	....
10,11	+633[a]	....	....	....	....	....	....	....	....	....	....	....
14	+640[a]	....	....	- 28	-553	....	+439	....	....	....	....	-340
15	+643	....	....	....	....	....	....	....	....	....	....	....
16	+644[a]	+503	+581	+ 21	....	+185	+449	....	....	+182	....	....
17	+646[a]	....	....	....	....	....	....	....	....	....	....	....
19,20	+648	....	....	....	....	....	....	....	....	....	....	....
20,21	+645	....	....	....	....	....	....	....	....	....	....	....
22	+646[a]	+507	+593	+ 53	....	+190	+443	- 33	....	....	....	....

The more distant stations to the north of the Volcano are S-162, S-163, S-164, and S-165. The variation of the values with time for these stations can be seen to be much greater than the variations of the stations in Zone A which are 11 miles from the Volcano. It can thus be said that the magnetic field was changing in the zone from three to seven miles north of the Volcano during June, July, and August.

The stations in Zone B near the Volcano are characterized by being erratic compared to Zone-A stations. Probably even more care was used in making the Zone-B measurements than in making the Zone-A measurements. The fact remains that at a point which is six miles north of the

Table 4--Relative values of vertical intensity at principal stations near Parícutin Volcano (concluded)
(Values from March 7 through April 17 are referred to Base 1, all others to Base 20)

Date	13	14	S-162	S-163	S-164	S-165	Base 20	21	22	23	24	25
1945												
Apr. 17	-990	-1536	....	....	....	....	....	....	....	....	....	....
19	....	....	....	....	....	....	0	-100	+351	-603	+305	+607
26	....	....	....	....	....	....	0	-105	+331	-624	+265	+563
27	-356	-894	....	....	....	....	....	....	....	....	....	....
May 7-8	....	....	....	....	....	....	0	- 94	+330	-614	+274	+573
9	-347	-885	....	....	....	....	....	....	....	....	....	....
18	-326	-859	....	....	....	....	....	....	....	....	....	....
26	-330	-862	....	....	....	....	....	....	....	....	....	....
27	....	....	....	....	....	....	0	-101	+338	-607	+289	+583
June 6	....	....	....	....	....	....	0	- 96	+336	-620	+286	+583
7	-311	-846	....	....	....	....	....	....	....	....	....	....
13	....	....	+851	+592[a]	-108[a]	+145	....	....	....	....	....	....
22	-330	-850	....	....	....	....	....	....	....	....	....	....
23	....	....	+846	+493	+122	+127	....	....	....	....	....	....
July 7	-320	-858	....	....	....	....	....	....	....	....	....	....
10	....	....	+827	+476	+115	+115	....	....	....	....	....	....
13	....	....	....	....	....	....	0	- 90	+322	....	+274	+550
17	....	....	+805	+454	+ 91	+ 93	0	....	....	....	....	....
18[e]	....	....	....	....	....	....	0	....	....	....	....	+540
23	....	....	+818	+464	+112	+108	....	....	....	....	....	....
25-26	....	....	....	....	....	....	0	- 93	+310	....	+264	+540
30	....	....	+837	+485	+111	+100	....	....	....	....	....	....
Aug. 7	....	....	+813	+464	+112	+109	....	....	....	....	....	....
8[f]	....	....	....	....	....	....	0	-103	....	....	....	....
10,11	....	....	....	....	....	....	....	- 93	+323	-628	+273	+558
14	-362	-878	....	....	....	....	....	....	....	....	....	....
15	....	....	....	....	....	....	0	....	....	....	....	....
17	....	....	+845	+490	+128	+124	....	....	....	....	....	....
19,20	....	....	....	....	....	....	0	-102	+319	....	+275	+570
20,21	....	....	+859	+497	+133	+121	0	....	....	....	....	....

---

[a] Base 1 was occupied on this day, but Base 20 was not; value assigned to Base 1 was derived by interpolation.

[b] Stations 8 and 9 were not exactly reoccupied; hence the values are not comparable and are not plotted on Figure 10.

[c] Observations at Stations S-163 and S-164 on June 13 have been rejected.

[d] June 26-28, [e] July 17-19, [f] Aug. 8-9.

Table 5--Relative values of vertical intensity at miscellaneous stations near Parícutin Volcano
(Values for March 7 and August 24 are referred to Base 1, all others to Base 20)

Date	II	III[a]	IV[a]	V[a]	G-1[a]	G-36	S-3	S-4
1945								
Mar. 7	+ 4	+ 29	- 96	- 19	....	....	....	....
May 10	+647	+678	+552	....	....	....	....	....
May 17	+667	+699	+563	+623	....	....	....	....
May 24	....	....	....	....	1007	+513	+ 85[a]	-154
May 26	+646	+697	+570	+624	....	....	....	....
May 29	....	....	....	....	+662	+517	+ 7	-153
June 6	....	....	....	....	+847	+521	+ 29	-153
June 23	....	....	....	....	+471	+494	+ 22	-161
July 21	....	....	....	....	....	....	+ 27	....
Aug. 10	+659	+659	+538	....	+814	+490	- 2	-163
Aug. 24	....	....	....	- 16	....	....	....	....

---

[a] Values at these stations uncertain, since values may not result result from exact reoccupation.

Volcano the field is apparently changing, and the values are erratic up to the cone itself, while those stations over 11 miles southeast of the Volcano show a slight drift and are not nearly so erratic as the stations in Zone B. The overall change during the period of the investigation for any one station was usually less than 50 gammas.

Station 4 is interesting because it was about 15 feet from the San Juan lava flow. During the dry season the station remained fairly constant, but during the rainy season the field began to increase erratically with reference to the Uruapan Base. The reason for this is not known; however, if the cooling rate of the lava flow is increased, an increase of vertical field should be expected.

While looking for an area of low gradient to establish the magnetic observatory, the readings given in Table 6 were made in the vicinity of the lower Casita and at its present location at the new Casita.

Table 6--Results of survey to determine low-gradient area

Date	Station	Reading	Z
1945		sc.-div.	γ
Feb. 24	300 feet SSW of Casita	- 0.25)	
	40 feet N of Casita	+ 54.30)	+ 715
	200 feet N of Casita	- 17.05)	- 936
	240 feet N of Casita	+ 64.4)	+1068
	15 feet W of line	- 15.2)	-1042

Where the Peons were digging the foundation for the new Casita, which is in the same locality as the above stations, readings similar to those listed were made. A large boulder of lava (two feet in diameter) was removed from the diggings and placed beneath the instrument. Without the boulder the instrument read -203 gammas, while with the boulder beneath the instrument it read -703 gammas, a difference of -500 gammas. This should illustrate the type of gradients that can be expected in this region.

The results of the absolute determinations at the Uruapan Base and the San Juan Base are summarized in Table 7.

Table 7--Absolute determinations at Uruapan Base and San Juan Base

Station	Date	Mean preliminary reduced values		
		D	I	H
	1945			γ
Uruapan	Apr. 5,6	+10° 28'.1	+45° 57'.0	30762
	June 9,10	+10 27.0	+45 57.1	30765
San Juan Base I	Mar. 14, 16, 20	+ 9 56.0	+46 14.1	31149
	June 11	+ 9 54.1	+46 10.3	31164

STEENLAND'S mean results for the Uruapan Station on July 2, 3, 1943 were: D, +10°28'.4; I, +45°59'.3; H, 30792γ.

Thus it can be said that no great changes have taken place in the magnetic field at Uruapan since 1943.

Conclusions

It is concluded that a slight warping of the magnetic field around Parícutin Volcano is taking place, with the change being barely noticeable 11 miles southeast of the Volcano, quite noticeable 6.6 miles north of the Volcano, and very noticeable from zero to three miles north of the Volcano where the field behaved erratically during the five months observations were made. It was also found that sudden changes may occur near cooling lava flows, and that gradients as high as 1000 gammas in 50 feet may occur over old lava flows.

Recommendations

This work should point the way to future investigations in magnetism at Parícutin, since it has been shown that spot values will tend to be erratic and reflect topography to such an extent that anomalies caused by subsurface structure will be masked. The author believes that further work would probably be most fruitful if two temporary observatories were set up, one at Uruapan and one near the Volcano. Then with adequate base-line control, the possible warping of the field could be studied. It is suggested that repeated profiles over relatively fresh lava flows may yield some knowledge of the cooling rate within the flow.

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PHASE RELATIONS IN THE SYSTEM SULFUR--SILVER AND THE TRANSITIONS IN SILVER SULFIDE

F. C. Kracek

Abstract--This paper presents the melting relations for the entire system sulfur--silver, together with a study of the transition behavior of silver sulfide. Silver sulfide melts at 838±2°C and undergoes two transitions in the solid state, each of which occurs at variable temperatures over a limited range of composition. The mean temperatures for the lower transition (Ag_2S III = Ag_2S II) are 177.8°C in sulfur-rich and 176.3°C for silver-rich preparations; for the upper transition (Ag_2S II = Ag_2S I) they are, respectively, 622°C and 586°C. A discussion is given of a possible mechanism for the incorporation of a limited excess of sulfur or silver into the lattice, as based on the semi-conducting properties of the substance and lattice disorder.

The melts of silver sulfide form two liquid layers with sulfur-rich melts at 740°C, and with silver-rich melts at 906°C. The eutectic with sulfur is at 119.3°C, and with silver, at 804°C.

Introduction

Chemical literature describes the preparation of three sulfides of silver, Ag_2S_2, Ag_2S, and Ag_4S. Only one of these, Ag_2S, occurs in the system S--Ag, as here presented, and in nature, where it is found in two mineral varieties, argentite, externally cubic, and the rarer monoclinic (or orthorhombic?) acanthite. These two varieties present some interest as a geological thermometer inasmuch as acanthite, the variety stable below the transition point of 176 to 178°C, could only have grown in well developed crystals below this temperature. This, and the minor role the compound plays as an ore of silver would hardly justify the extensive amount of experimental work devoted to it in the past; it is important, however, as a representative of an extensive series of "sulfide" compounds with somewhat complex physical and chemical properties, which have not yet been completely elucidated.

In the binary system sulfur--silver, thermal studies have previously been made [FRIEDRICH and LEROUX, 1906; JAEGER and VAN KLOOSTER, 1912; BISSETT, 1914; URAZOV, 1915] of only that portion which extends from Ag_2S to Ag; studies of the sulfur-rich portions of the system have not been attempted probably because of the difficulty of retaining sulfur in the preparations at elevated temperatures when its vapor pressure is high. A method has been found to overcome this difficulty, and the present paper gives results of measurements for the entire system. It has been found as well that the polymorphous transitions of silver sulfide present certain uncommon features, and a study of these is described in detail and discussed in relation to other properties of the compound.

Experimental part

The apparatus--Measurements of phase-reaction temperatures were made by differential thermal analysis in a pressure apparatus which permits safe heating of sealed containers filled with the preparations even when considerable vapor pressures are developed in the samples.

Fundamentally, the apparatus is an electrically heated pressure-tight tubular vessel or "bomb" which can be connected to a source of pressure. Within the bomb itself the sample is heated in a hermetically-sealed reaction vessel in intimate contact with the reading junction of a differential thermocouple for measuring the temperature and detecting reaction arrests. Provisions are made for adjusting the pressure in the pressure vessel at the proper value to counterbalance approximately the bursting effect of the vapor pressure of the sample, when this becomes dangerously high.

The details of construction of the apparatus will be evident from Figures 1 and 2. The body of the bomb is of 28 per cent chrome-iron, in that portion which enters the furnace, and of malleable iron pipe fittings elsewhere. A "railroad" pipe union with a brass seat provides a demountable pressure-tight joint, which has proved very reliable in practice. The thermocouples are led into the bomb through a packing of alternate layers of limestone and talc, similar to packings used for work at extreme pressures. This packing was assembled by compression at 10,000 lbs/in^2.

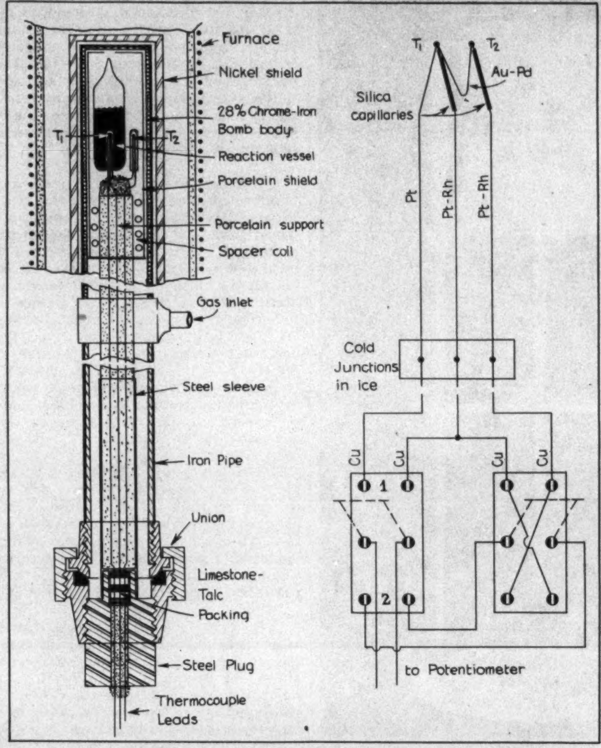
Furnace
Nickel shield
28% Chrome-Iron Bomb body
T1
T2
Reaction vessel
Porcelain shield
Porcelain support
Spacer coil
Gas inlet
Steel sleeve
Iron Pipe
Union
Limestone-Talc Packing
Steel Plug
Thermocouple Leads
T1
T2
Au-Pd
Silica capillaries
Pt
Pt-Rh
Pt-Rh
Cold Junctions in ice
Cu
Cu
Cu
Cu
1
2
to Potentiometer

Fig. 1--Diagrammatic representation of an apparatus for thermal analysis under controlled pressure

The switching arrangement for thermocouples is shown at the right of Figure 1. This enables either the measuring or the differential thermocouple to be connected to the potentiometer, which is a Wolff-Feussner, connected to a sensitive mirror galvanometer critically damped at a sensitivity of one microvolt per scale division. The whole apparatus is electrically shielded, so that tenths of a division can be estimated with certainty in measuring relative displacements of the galvanometer mirror.

The reaction vessel is an ampule, of the form shown in Figure 1, made of silica glass, which does not react with sulfide mixtures. For reproducibility of the thermal effects, the ampules are all blown to approximately the same dimensions, being made of seven mm internal diameter tubing; the re-entrant thermocouple well is 15 mm long. The sample is sealed in under a vacuum. The strength of the ampules is sufficient to withstand a pressure unbalance of considerably more than ten atmospheres, as determined by actual tests.

Pressure in the bomb is regulated by means of a reducing valve, connection being made to a tank of carbon dioxide as the source of pressure.

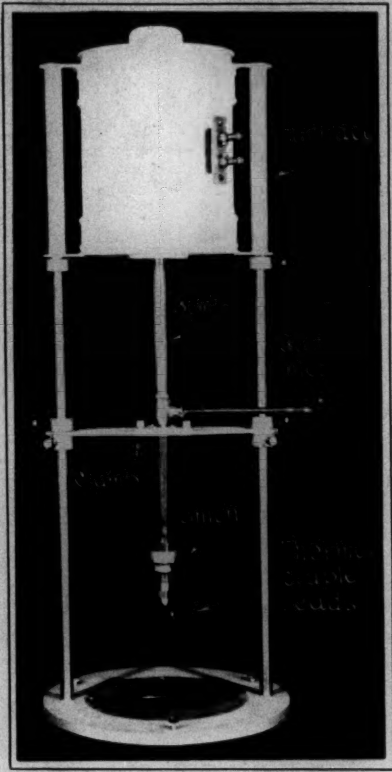

Fig. 2--A view of the assembled apparatus

The assembled apparatus is shown in Figure 2. Vertical adjustment is provided for the furnace and the bomb to allow the sample to be brought to the position of best temperature distribution in the furnace. Since the chrome-iron body of the bomb, with its low thermal conductivity, acts as an effective thermal insulator, a nickel tube is interposed between the inner wall of the furnace and the bomb to act as a heat-distributing shield.

For measurements when pressure control is not needed, an apparatus of the type shown in Figure 3 can be used. For low temperatures, the hollowed-out block B and the furnace F are of copper, the winding being of asbestos-insulated nichrome. This arrangement can be used up to 300°C. For higher temperatures, a similar block of monel metal, placed in a two-inch tubular furnace, can be used to well above 700°C without excessive oxidation. The sample container A may in this case be of Pyrex glass for work up to 550°C. The identical thermocouples θ_1 and θ_2 are connected by a suitable switching mechanism to the potentiometer, reading the differential temperature $\theta_1 - \theta_2$ when connected in opposition.

Thermocouple calibrations--Calibrations of the thermocouple are made at a number of points (in this instance, at the melting points of tin, zinc, and silver) and the thermocouple emf readings, after applying proper corrections, are converted to temperatures on the International Temperature Scale in accordance with tables published by the National Bureau of Standards.

Reagents--Silver sulfide was prepared from mint silver, 999.9 fine, purchased from the United States Mint, and from crystallized sulfur, by heating at about 500°C, in sealed tubes of Pyrex or silica glass. Other mixtures employed in the work were made up quantitatively by adding weighed quantities of sulfur or silver to the sulfide, and sealed under a vacuum in the reaction ampules for study.

Measurement of phase-reaction temperatures--The measurements were performed by differential thermal analysis, by means of both heating and cooling-curve runs. Because of hysteresis (superheating, undercooling) the temperatures of the cooling-curve arrests usually lie somewhat below those of the heating-curve arrests, and the equilibrium phase-reaction temperature lies at some point within the hysteresis zone. The equilibrium temperature in these measurements is arbitrarily assumed to be the arithmetical mean of the corresponding heating and cooling curve arrests, and the probable error is indicated. This is emphasized because, by tradition, thermal-analysis data even today are usually obtained from cooling-curve data only. The resulting error may be negligible for prompt reactions, but for sluggish reactions it may be large, and what is more important, unknown in magnitude.

Method for solubility of silver sulfide in sulfur--Solubility of silver sulfide in sulfur is very small and could not be determined by thermal analysis. Measurements of the solubility were therefore made by chemical analysis. For this purpose, mixtures of sulfur and silver sulfide were enclosed in tubes of two to three mm internal diameter, and rotated in a furnace at the desired

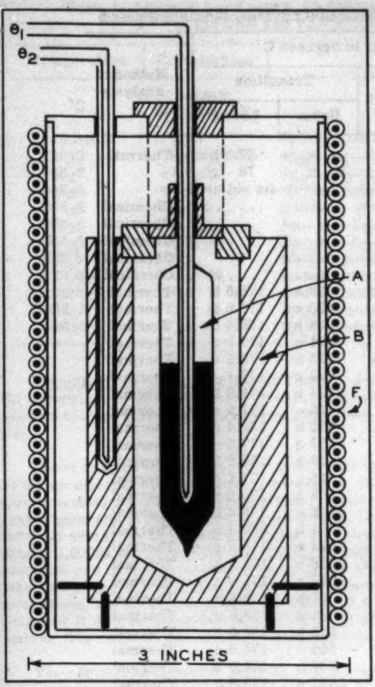

Fig. 3--A diagram of an apparatus used for thermal analysis when pressure control is not needed, especially at moderate temperatures

constant temperature until equilibrium was reached. To separate the solution from the undissolved sulfide, the tube was then held stationary in the proper position until the solution drained from the crystals which adhere to glass (either Pyrex, or silica). The tube was then removed from the furnace, quickly cooled, and the contents analyzed. The sulfide dissolved in the sulfur was determined by weighing the residue left after evaporating the sulfur in a vacuum; this result was further checked by evaporating the sulfur from the undissolved sulfide and weighing to determine the loss by solution. The two determinations in each experiment usually checked to within 0.05 mg.

Experimental results

The temperature-composition diagram--The results of our measurements of the liquidus and other significant temperatures in the system, principally in the newly explored region from sulfur to silver sulfide, but also including a few compositions in the region between silver sulfide and silver, are collected in Tables 1 and 2. A combination of these with the results of previous workers yields the temperature--composition diagram of Figure 4.

At the liquidus there are two regions of liquid immiscibility. In the sulfur--silver sulfide portion of the system, the two liquids are in equilibrium with the crystalline sulfide at 740±2°C and have the compositions 0.035±0.005, and 64.0±0.2 atomic per cent Ag. These were evaluated from the data by graphical interpolation.

In the partial system silver sulfide--silver the two liquids coexist with metallic silver at 906±1°C (previous values range from 897 to 906°C), and the compositions of the two liquids at this temperature are 68.9±0.2 and 94.2±0.3 atomic per cent Ag. The value for the silver-rich layer is interpolated from the literature, most weight being given to the data of URAZOV [1916] and of JAEGER and VAN KLOOSTER [1912]. The composition of the sulfide-rich layer is newly determined, the previous data having given values between 68 and 70 atomic per cent Ag.

There are two eutectics in the system. The previously known eutectic with silver sulfide and silver as solid phases is at 804±1°C, older values ranging from 798 to 806°C, and the composition of the liquid is 68.0±0.3 atomic per cent Ag, as determined from the data of URAZOV and of JAEGER and VAN KLOOSTER [1912].

The temperature of the other eutectic, with sulfur and silver sulfide as solid phases, coincides, within the error of measurement, with the melting point of monoclinic sulfur, which was found to be 119.3±0.2°C. The liquid in coexistence with the crystals is practically pure sulfur.

Two other melting points of sulfur were observed. These are (1) 105.5°C for "nacreous" sulfur, and (2) 112.3°C for a pale yellow form which may be rhombic sulfur [MELLOR,1930]. Rhombic sulfur was found to transform to monoclinic at 97.5±0.5°C, and on cooling, the reverse transformation took place at 78°C. Liquid sulfur gave an arrest on heating at 160 to 164°C, depending on the rate of heating; on cooling, it gave no perceptible arrest but the differential temperature began to deviate at temperatures below 160°C. These observations are recorded here for the sake of completeness, without discussion, as all these transformations have previously been observed by others.

Table 1--Temperature--composition data, sulfur--silver, this investigation

Per cent silver		Temperatures in degrees C		Transition		Method of analysis
Weight	Atomic	Liquidus	Eutectic	Upper	Lower	
0	0	119.3 h	....		97.5 h 78 c (in sulfur)	Thermal
0.033	0.010	210	....	...	....	Chemical
0.067	0.020	558	....	...	....	Chemical
0.081	0.024	578	....	...	....	Chemical
0.108	0.032	629	....	...	....	Chemical
0.118	0.035	731	....	...	....	Chemical
6.11	1.90	741 h	119.3 h	623 h	178.5 h	Thermal
		739 c	....	620 c	177.0 c	Thermal
45.35	19.78	740 h	119.0 h	624 h	178.4 h	Thermal
		738 c	....	621 c	177.2 c	Thermal
71.13	42.27	742 h	119.1 h	623 h	178.5 h	Thermal
		739 c	....	622 c	177.1 c	Thermal
81.58	56.82	741 h	119.2 h	624 h	178.3 h	Thermal
		740 c	....	620 c	177.5 c	Thermal
85.9[a]	64.4[a]	758 h	119.3 h	622 h	178.4 h	Thermal
(85.44)	(63.55)	755 c	....	622 c	177.5 c	Thermal
86.6[a]	65.7[a]	817 h	....	618 h	178.5 h	Thermal
(86.47)	(65.52)	815 c	....	618 c	177.1 c	Thermal
86.8[a]	66.1[a]	828 h	....	608 h	178.0 h	Thermal
(86.75)	(66.05)	828 c	....	606 c	176.4 c	Thermal
87.06	66.67	838 h	....	593 h	176.7 h	Thermal
		838 c	....	593 c	175.8 c	Thermal
87.73	68.00	805 h	805 h	588 h	176.5 h	Thermal
		803 c	803 c	586 c	175.9 c	Thermal
88.12	68.80	900 h	804 h	587 h	176.6 h	Thermal
		895 c	802 c	585 c	175.6 c	Thermal
92.52	78.64	906 h	804 h	586 h	176.2 h	Thermal
		906 c	804 c	586 c	174.9 c	Thermal
95.39	86.02	906 h	805 h	587 h	176.5 h	Thermal
		905 c	803 c	587 c	175.6 c	Thermal
100.00	100.00	960.5	....	...	....	Thermal

[a] Composition at the liquidus corrected for sulfur in vapor space. The corresponding composition by synthesis is in parentheses.

h = heating arrest.
c = cooling arrest.

Melting point of silver sulfide--Ag_2S melts, according to JAEGER and VAN KLOOSTER, at 842°C; URAZOV gives the same value for the freezing point of a preparation of 13.07 weight per cent of S, equivalent to 66.40 atomic per cent Ag. The above results were obtained with melts in open containers. Other values in the literature range as low as 812°C; many of these are evidently in error because of failure to protect the melts against oxidation.

According to our measurements with the sealed ampules, silver sulfide melts and freezes at 838 ± 2°C. The same value was obtained by EINAR JENSEN at this Laboratory with separately prepared samples and different thermocouples and heating apparatus.

Calculations of the latent heat of melting of silver sulfide from values of melting point lowering in different systems yield highly discordant results [KELLEY, 1936], most probably because of deviations from thermodynamic ideality presupposed in the calculations. The calculated values range from 900 to 3600 cal/mole. The value derived from the lowering of the melting point of silver sulfide by sulfur, assuming S_4 and Ag_2S molecules, is of the order of 900 cal/mole, near the lower limit of the range. No calorimetric measurement of this quantity is as yet available.

Table 2--Isobaric fixed points, as deduced from Table 1 data combined with data of JAEGER and VAN KLOOSTER, and of URAZOV

Temperature	Composition	Reaction
°C	Atomic per cent Ag	
119.3±0.2	0.00	Melting point, sulfur; also sulfur--silver sulfide eutectic
740±2	0.035±0.005	Ag_2S--L_I--L_{II}--V, sulfur-rich liquid
740±2	64.0±0.2	Ag_2S--L_I--L_{II}--V, sulfide-rich liquid
838±2	66.67	Melting point, silver sulfide
804±2	68.0±0.3	Eutectic, silver sulfide--silver
906±1	68.9±0.2	Ag--L_I--L_{II}--V, sulfide-rich liquid
906±1	94.2±0.3	Ag--L_I--L_{II}--V, silver-rich liquid
960.5	100	Melting point, silver, International Temperature Scale
177.8±0.7	0 to 66	Lower transition in sulfur-rich silver sulfide
176.3±0.5	66.67 to 100	Lower transition in silver-rich silver sulfide
622±3	0 to 65.3	Upper transition, sulfur-rich silver sulfide
586±3	67.1 to 100	Upper transition, silver-rich silver sulfide

Transitions in silver sulfide--In Tables 1 and 2 and Figure 4 we present some new data for the transitions in silver sulfide. There are three modifications, which we have labeled with Roman numerals; their relationship to known properties of silver sulfide is considered in some detail below.

There are two transitions. The lower transition is that between the modifications III and II; so far as external symmetries are concerned, these modifications are preserved in nature as argentite (cubic) and acanthite (monoclinic), mentioned in the introduction. The transition, so far as rearrangements in the lattices are concerned, is prompt and occurs between 176 and 178°C; the external symmetry is preserved during the transition, probably because the volume change is very small, 0.00065 cm^3/gm [KIMURA, 1934], so that no great strains are involved. Cubic crystals of argentite are in reality acanthite paramorphs after argentite. The unit cell of the low-temperature (acanthite, Ag_2S III) modification has been determined by RAMSDELL [1943, 1925, 1927] to be monoclinic, $a = 9.47A$, $b = 6.92A$, $c = 8.28A$, $\beta = 124°$, with $z = 8$; the character of the unit cell is such that it may be described also in terms of orthorhombic or cubic indices, with a close approximation; this accounts for acanthite being variously reported orthorhombic or pseudo-cubic.

The second modification, Ag_2S II, stable above the lower transition and responsible for the external symmetry of argentite appears from X-ray studies to be cubic, $a_o = 4.88 \pm 0.02A$, with $z = 2$, according to RAHLFS [1935]. The structure worked out for it is a body-centered, slightly expanded close-packing of the sulfur ions, with the silver ions statistically distributed among 42 possible sites in this lattice. The structure is, according to this view, ordered with respect to sulfur ions, and disordered with respect to silver.

The upper transition was discovered by URAZOV [1915], who found a cooling arrest in the range 576 to 580°C in the presence of excess silver. In compositions near silver sulfide itself the arrest rose sharply to 592°C. This behavior is closely reproduced by our own results, which yield for the transition temperature as determined by both heating and cooling curve measurements 586±3°C in the presence of excess silver, and 622±3°C when sulfur is in excess. The transition temperature is variable for compositions in a narrow range about the composition of the compound itself, as may be seen in Figure 4. The behavior is further illustrated in Figure 5 for four different preparations. The extreme limits of composition over which the transition occurs at variable temperatures are, as determined from a large-scale diagram, 65.3 and 67.1 atomic per cent Ag, corresponding to the formulae $Ag_{1.882}S$ and $Ag_{2.040}S$.

The lower transition shows a similar, but much less pronounced variability in the transition temperature. Here the mean transition temperatures are 177.8±0.7°C with excess sulfur and 176.3+0.5°C with excess silver (see Fig. 6).

The variability in transition temperatures, both at the upper and the lower transition implies that silver sulfide in its various modifications is not a substance of invariable composition, but rather that it is able to accommodate in its respective lattices a limited excess of sulfur or silver ions. A number of such "non-stoichiometric" compounds are known; all of them appear to be semi-conductors, that is, ionic crystals in which electric current is carried largely, if not exclusively, by electrons rather than by diffusing ions [SEITZ, 1940; MOTT and GURNEY, 1940]. Silver sulfide appears to be a nearly pure electronic conductor in modification III and a mixed conductor [TUBANDT and REINHOLD, 1931; TUBANDT, 1933; WAGNER, 1933; KLAIBER, 1929] in modification II; nothing is yet known concerning the electrical or other properties of modification I except its melting point.

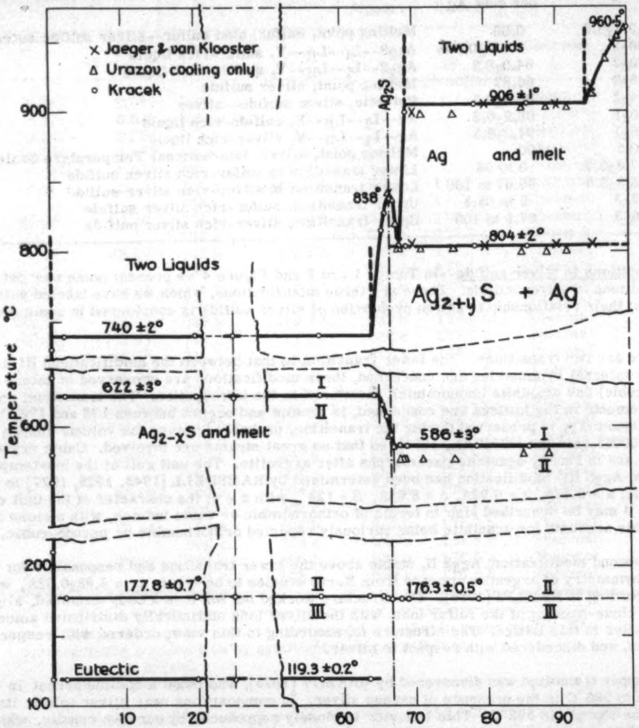

Fig. 4--The thermal diagram of the system sulfur--silver. The vertical and the horizontal scales have both been interrupted to allow the essential features to be presented on a larger scale

So far as Ag_2S II is concerned, there seems little doubt that it belongs to the class of compounds which possess an inherently disordered structure. This view is necessitated not only by the already mentioned results of X-ray analysis, but also by the abnormally high mobility of silver ions disclosed by the results of TUBANDT and coworkers on its electrical conductivity and transference numbers. WAGNER reconciled the high silver transfer with the predominantly electronic nature of the conductivity, determined by KLAIBER, by determining that the silver transfer resulted from an abnormally high rate of self-diffusion of silver ions. The conductivity of stoichiometric or slightly silver-rich Ag_2S II has a negative temperature coefficient and the HALL Coefficient is also negative; this would indicate not only that the conductivity is in a large measure electronic, but also that the substance might be classed as a true, if poor, metallic conductor, with the electrons not created by thermal excitation, but belonging to the whole crystal. On this view, L. W. NORDHEIM writes (by letter), "the valency electrons of the silver are only partially taken up by the sulfur atoms, the rest forming conduction electrons. This corresponds to the usual statement that the binding is only partially ionic." The conductivity of Ag_2S II is known to be sensitive to composition, being decreased by a factor of ten or more on heating in an atmosphere of sulfur vapor; "this effect can be understood simply as a change of supply of conduction electrons while the degree of ionization of S and Ag atoms, that is, the character of the binding need not be greatly influenced. The unbalance of charge due to excess ions of definite sign could be compensated by an electric polarization extending over a considerable volume, and not necessarily by trapped electrons or holes, as postulated by certain investigators. The number of conduction electrons need not be so very small since the disordered state of the lattice produces automatically a high and nearly temperature-independent resistance as observed."

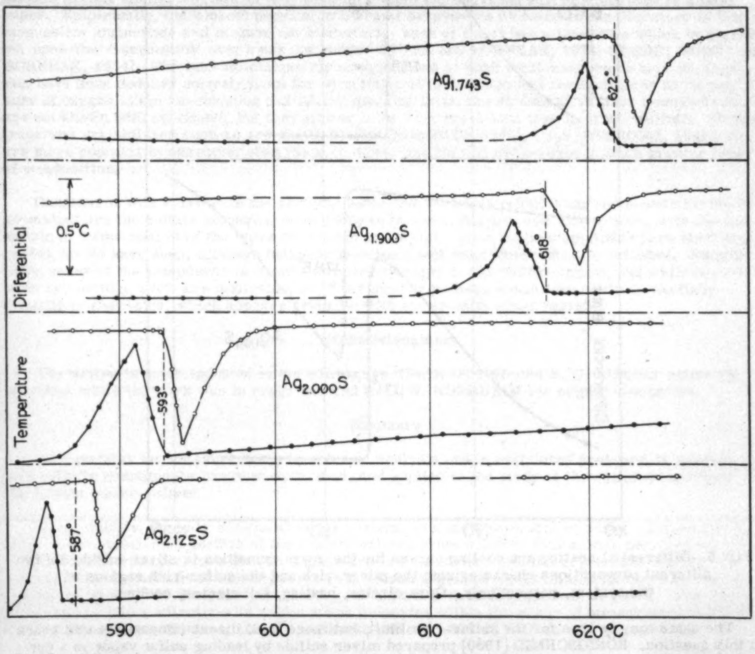

Fig. 5--Differential heating and cooling curves for the upper transition in silver sulfide in four different gross compositions as indicated. Open circles, heating; full circles, cooling.

From the point of view of thermodynamics the observed departures in composition of Ag_2S II from the stoichiometric may be regarded as a limited region of solid solutions. At the transitions there must of necessity be small regions of heterogeneity within which Ag_2S II coexists with one or the other modification, each of a different composition from that prevailing in Ag_2S II at the appropriate temperature within the transition range. It has not been possible experimentally to establish these heterogeneous regions in detail; hence Figure 4 merely indicates the variability of the transition temperatures.

With decreasing temperature the silver-rich limit appears to approach closer to the theoretical composition of the compound, as might be expected because of the less pronounced disordering effect of thermal vibrations. Empirically, this is made evident by the extrusion of hair silver, which always occurs at the cooler end of a silver-rich ingot heated in a furnace with a large thermal gradient. The formation of hair silver has already been discussed by URAZOV on this basis.

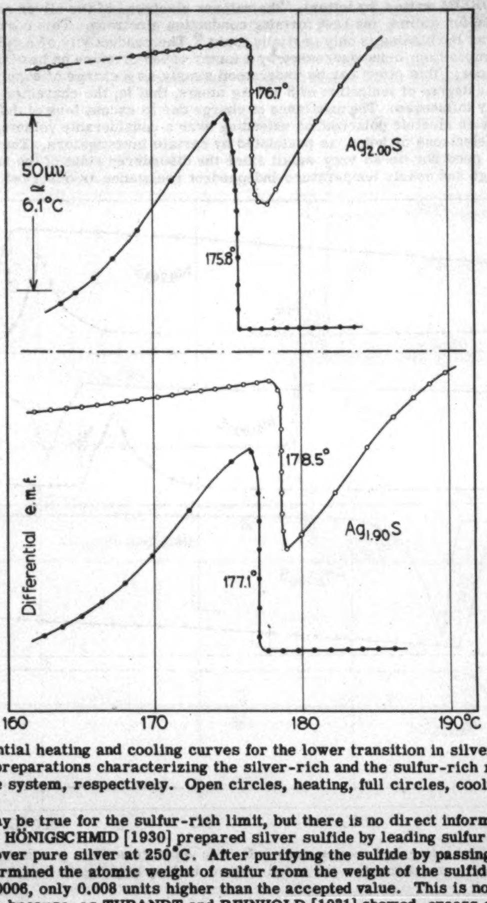

Fig. 6--Differential heating and cooling curves for the lower transition in silver sulfide for two different preparations characterizing the silver-rich and the sulfur-rich regions of the system, respectively. Open circles, heating, full circles, cooling.

The same may be true for the sulfur-rich limit, but there is no direct information that bears on this question. HÖNIGSCHMID [1930] prepared silver sulfide by leading sulfur vapor in a current of nitrogen over pure silver at 250°C. After purifying the sulfide by passing nitrogen over it at 200°C, he determined the atomic weight of sulfur from the weight of the sulfide formed, and found 32.0685±0.0006, only 0.008 units higher than the accepted value. This is not entirely conclusive, however, because, as TUBANDT and REINHOLD [1931] showed, excess sulfur is quickly removed from silver sulfide by a current of nitrogen. They also found that the change of electrical conductivity as a function of the pressure of sulfur vapor persists all the way down to the lower transition.

No measurements are available to determine whether low-temperature silver sulfide (modification III) is influenced in its properties by contact with either sulfur or silver. Its electrical conductivity is very low and apparently purely electronic. The crystals yield a complex X-ray diffraction pattern [RAMSDELL, 1927] which is the same for either the argentite or the acanthite variety. This information would indicate that Ag_2S III has a highly organized normal lattice; such a lattice would probably not dissolve either sulfur or silver in excess to any appreciable extent.

It is of interest to note that Ag_2S II, which exists only in the disordered state, transforms abruptly into the ordered modification III before it has the chance to become ordered itself. Similar behavior has been observed in the transformation of cubic NH_4NO_3 I into the tetragonal modification NH_4NO_3 II [HENDRICKS, POSNJAK, and KRACEK, 1932]. The more frequently encountered case is that of a gradual transition from an ordered state to a disordered one within a phase or a gradual transition followed by an abrupt one, as in the examples afforded by the ammonium halides, hydrogen halides, sodium nitrate, or quartz [EUCKEN, 1939].

Behavior such as is outlined here for silver sulfide is not common, even though many examples are now known of the so-called non-stoichiometric compounds. Silver selenide and the silver tellurides exhibit similar variations in transition temperatures; these will be discussed in a later paper. Empirically, the closest parallel in thermal behavior to be found in the literature is that of magnesium antimonide and magnesium bismuthide, each of which has a transition which is dependent upon the composition over a narrow range [GRUBE and BORNHAK, 1934; GRUBE, MOHR, and BORNHAK, 1934]. The non-stoichiometric compositions of such semi-conductors as ZnO, Cu_2O, etc. have been deduced entirely from the sensitivity of their electrical conductivities to the pressure of oxygen in the surrounding gas space; quantitatively, the variations in their compositions are not known with exactness, but they appear to be very much less than in silver sulfide. Finally, transition variabilities such as are shown by FeS [ROBERTS, 1935], Cu_2S [BUERGER, 1941], etc. are more complex in character than those in silver sulfide and extend over a much greater range of composition.

Considered with relation to the periodic table, the elements constituting compounds having such anomalies are the metals belonging principally to the iron, copper, and zinc groups, with the non-metals or semi-metals of the types of arsenic and sulfur. Both magnesium and oxygen must be included, as we have seen, although magnesium oxide itself most likely is to be excluded. Empirically, many of the compounds in question absorb strongly in the visible region, and while most of them are brittle, a few are malleable, as if the binding in these cases were at least partially metallic in character, which appears probable with silver-rich silver sulfide.

Acknowledgment

The writer is much indebted to his colleagues EINAR JENSEN and E. G. ZIES for active cooperation while the work was in progress, and to L. W. NORDHEIM for helpful discussion.

Summary

An apparatus for measurements by thermal analysis under controlled pressure on preparations with volatile constituents has been described, and applied to the study of the sulfur-rich region of the system sulfur--silver.

Silver sulfide, the only compound in the system, is almost insoluble in sulfur. Liquid insolubility in the sulfur-rich portion of the system extends from 0.035 to 64.0 atomic per cent Ag, at 740°C, at which temperature the two liquids are in coexistence with the crystalline sulfide. In compositions beyond silver sulfide, there is a second region of liquid immiscibility, with the two liquids, of 60.9 and 94.2 atomic per cent Ag, in contact with metallic silver at 906°C. The compound enters into a eutectic with sulfur which coincides within the error of measurement with the melting point of this element, 119.3°C, and with silver at 804°C, 68.0 atomic per cent Ag.

Silver sulfide has two transitions, the temperatures of which depend upon the presence of either excess sulfur or excess silver. The two mean limiting temperatures for the upper transition are 622 and 586°C; for the lower transition they are 177.8 and 176.3°C. In both cases the higher temperature corresponds with the presence of excess sulfur. A discussion is given of a possible mechanism for the incorporation of a stoichiometric excess of sulfur or silver into the lattice, as based on the semi-conducting properties and defect lattice of the intermediate modification of the compound.

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SOME FACTORS THAT INFLUENCE THE ACCURACY OF WATER-SUPPLY FORECASTING IN THE INTERMOUNTAIN REGION

A. R. Croft

Abstract--This paper presents data on precipitation, accumulation and melting of snow, year-long soil moisture, and stream flow from north- and south-facing slopes of a small drainage basin in the Wasatch Mountains of Utah.

The data suggest the following reasons why water content of snow on April 1 may not be a reliable index of water yield in this area: (1) Water content of the soil mantle, which must be raised to field-moisture capacity before water is available for stream flow, varies on April 1 from year to year; (2) the moisture deficit in the mantle may be partly overcome by rainfall before snow begins to accumulate, thus making more of snowpack water available for stream flow; (3) melting of snow during winter, especially on south-facing slopes, also aids in overcoming the moisture deficit in the soil; (4) spring rainfall (inch for inch) is more effective in generating stream flow than equal amounts of precipitation during October to March; (5) rapid melting of snow results in greater water yield than slow melting. The data also suggest the need for further study of snow-course locations.

The problem of forecasting stream flow

Forecasting the annual water supply for irrigation, industrial, and urban needs in the arid valleys of the West by using the water content of snow on watersheds in April has become a very useful practice. Although these forecasts have given results of great practical value, they have been, at times, considerably in error. Seeking to minimize error, forecasters have used various additional data to correct for discrepancies between water supply indicated by the water content of snow on April 1 and measured runoff.

Refinement in the use of data on snow alone, consisting of weighting the water content of snow by zones differing in elevation, has been used by ELGES [1939] and others; and valley precipitation in lieu of snow in drainage basins, has been used by ALTER [1940]; water level in shallow wells by ELGES [1940]; departures of temperature from normal during spring runoff by WORK [1944]; and October runoff by EAGLE [1939]. Fall precipitation has been used by MONSON [1939] and FARROW [1939]; spring precipitation by CLYDE and WORK [1943], PAGET [1938], and CHURCH and BOARDMAN [1943]; fall and spring precipitation by OLSEN and PRICE [1943].

Clarification of some of the reasons why the water content of snow on watersheds on April 1 is not a wholly reliable index of runoff came out of studies of stream-flow characteristics and year-long soil moisture under different covers of vegetation at the Wasatch Branch of the Intermountain Forest and Range Experiment Station. Had a study been designed especially to determine the factors that influence water-supply forecasting, additional, and in some respects more detailed, data would have been obtained.

This paper discusses some of the major factors, in addition to water content of snow on April 1, that are shown by available data to influence total runoff and stream-discharge characteristics and which, accordingly, are important in water-supply forecasting.

The area studied

Data in this report were obtained on Farmington Drainage comprising 6500 acres of typical range and water-yielding land on the west slope of the Wasatch Mountains in northern Utah. Vegetation consists of brush and herbaceous plants on south-facing slopes and aspen-fir timber with scattered patches of chaparral on north-facing slopes. A mantle composed of disintegrated granite gniess, varying in depth from a few inches at high elevations to many feet at low elevations, covers most of the drainage. Soil, which varies in depth from a few inches to a few feet, is a sandy-gravelly loam lacking in distinct horizonal differentiation. Content of organic matter is high; in the first inch of the surface it varies from about 3 to 20 per cent.

Methods used and data obtained

Stream flow--Stream flow from Farmington Drainage was measured near its mouth at 5000-foot elevation, using a masonry control in the stream channel equipped with an automatic water-stage recorder. Stream flow was measured also from Whipple Tributary, a south-facing drainage of 359 acres, and from Miller Tributary, a north-facing drainage of 252 acres, using Venturi flumes equipped with water-stage recorders.

Snow storage--The amount of snow in storage was measured at three courses--two in Farmington Canyon at 7000-foot elevation, and at a third near the mountain crest at 8300-foot elevation. The two courses at 7000 feet were only about 500 feet apart, one on a north-facing slope of 40 per cent in aspen-fir cover, and the other on a slope of 40 per cent in brush and herbaceous cover. The high 8300-foot course is in sagebrush cover on a west slope of eight per cent. Measurements were made monthly with a Utah snow-sampling tube from November through March, and weekly or oftener after April 1.

Precipitation--Precipitation was measured throughout the year with storage-type gages, and from April to November with an intensity gage, located near the snow courses at 7000-foot elevation.

Soil moisture--Soil moisture was measured throughout the year at the two 7000-foot snow courses. Moisture in both mantles was obtained to a depth of six feet using specially constructed soil-moisture sampling pits that could be entered, even when deep snow covered the ground, by passageways that project upward through the snow (Fig. 1). Samples were obtained from depths below the surface of 3, 6, 9, 12, 18, 24, 36, 48, 60, and 72 inches.

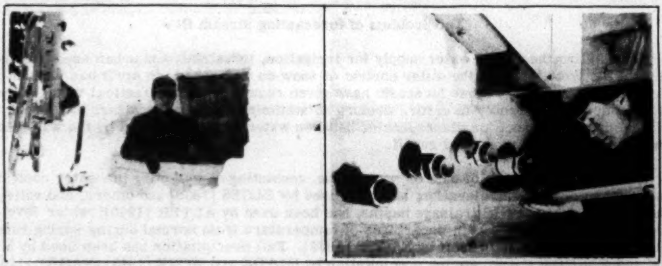

Fig. 1--Man in passageway to soil-moisture sampling pit (left) and interior of pit showing observer removing soil sample from sampling tube

The capillary moisture content of the entire six-foot soil mantle, obtained in per cent of dry weight of soil, was converted to volume of water on the basis of an average soil weight of 88 pounds per cubic foot. The capillary moisture content of the mantle at field capacity, as used in this paper, is the moisture content at each of the sampling depths one week after gravitational water had disappeared from the soil. Values shown on the accompanying charts represent the average moisture content of the entire six-foot soil mantle.

Capillary water in the six-foot mantle was divided into "removable" and "nonremovable" water. That part of the total capillary water that was removed each summer by evaporation and transpiration was considered to be removable, and that part which remained was considered to be nonremovable. For example, the average moisture content of the south-facing six-foot mantle was 17 inches at field capacity and five inches at the lowest observed moisture stage. Accordingly, 12 inches of water is considered to be removable by evaporation and transpiration and the remaining five inches nonremovable. The amounts shown on the charts are approximate. However, because soil moisture was reduced about the same amount each summer, and since the loss in late August and in September was extremely slow, it is believed the figures given represent close approximations of the amount of water that can be removed from the respective mantles by evaporation and transpiration, and the amount that cannot be removed.

Time of occurrence of gravitational water throughout the six-foot mantle was obtained also. If water dripped from the sampling pipes or if it could be pressed out of a soil sample with the fingers, gravitational water was assumed to be in the soil.

Temperature--Temperature was measured by a thermograph checked with maximum and minimum thermometers in a standard instrument shelter located about midway between the north- and south-facing sites where snow and soil moisture were measured.

Relation of water stored in snow to annual runoff

There is no consistent relationship between annual runoff from Farmington Watershed and the amount of water stored in snow as obtained by surveys at any of the three snow courses (Table 1). Water stored as snow at the 8300-foot west-facing course was almost a third more on April 1 of the year runoff was least (23.9 inches), than it was on March 25 of the year runoff was greatest (27.6 inches). The north-facing 7000-foot course had about the same amount of water stored as snow in both years and thus it did not reflect differences of runoff.

Table 1--Precipitation from October to March at 7000-foot elevation[a], water content of snow at three snow courses, and annual runoff from Farmington Drainage, 1942-43 and 1943-44

Item	Year	
	1942-43	1943-44
Date of snow survey	April 1	March 25
Precipitation from October to March at 7000-foot snow courses (inches)	27.7	25.9
Farmington Creek runoff (inches)	23.9	27.6
Water content of snow (inches)		
West-facing snow course, elevation 8300 feet, sagebrush cover	26.1	20.0
North-facing snow course, elevation 7000 feet, aspen-fir cover	20.3	19.8
South-facing snow course, elevation 7000 feet, low brush cover	3.8	8.9

[a] Precipitation at 8300-foot snow course not known

As shown in Table 1, the south-facing course at 7000-foot elevation had the largest amount of water in storage the year runoff was largest, but there is some question as to its significance because, here, with an increase of 130 per cent in available water only an increase of ten per cent in runoff occurred. Then, too, since the amount of snowfall on the north- and south-facing courses was about the same, the amount of water in storage at the south-facing course reflects the amount of winter melting more than it does the water available for stream flow. Finally, since this course, as a result of winter melting, may be bare of snow on April 1, its value in forecasting stream flow is obviously questionable.

Another, though probably less significant, inconsistency between snow storage and runoff was the occurrence of two distinct periods of high runoff, one of which cannot be related to snow melting because it occurred when only about five per cent of the drainage was snow covered (Fig. 2). The first period of high runoff was obviously caused by melting snow, because the drainage had a snow cover of 40 per cent when peak runoff occurred. On the other hand, because the second period occurred during a series of rainstorms after all but about five per cent of the snow cover was gone, it is clear that rain and not melting snow was the cause.

Factors that influence water yield

Some of the important reasons why the amount of water stored as snow about April 1 is inadequate as a single factor-index of runoff and discharge from Farmington Watershed were suggested by data on stream flow, snow accumulation, and soil-mantle moisture from the north- and south-facing slopes of Farmington Watershed, by the character and seasonal distribution of precipitation, and to a limited extent by temperature. In keeping with the object of this paper the following discussion is made under headings of the major factors that the data suggest are related to runoff. These factors are: Water storage in the soil mantle; recharge of mantle moisture by October precipitation; recharge of mantle moisture by winter snow melting; loss of water by deep seepage; and spring rains. Location of snow courses, so as to obtain the most reliable index of available water, is considered also.

Although some of these factors are shown to be more closely related to runoff than others, no attempt is made at this time to say which may be used in stream-flow forecasting and which cannot; nor is an attempt made to set up specific procedures for using any of them in forecasting runoff, as it is felt that such procedures must await further study. The following discussions are intended primarily to point out some basic concepts involving the relationship of runoff from a drainage to some of the important factors that influence water yield.

Water storage in soil mantle--Two of the most significant factors related to water-supply forecasting brought out by the studies on Farmington Watershed are: (1) Practically all water from rains or melted snow passes through the soil mantle before it becomes available for stream flow; and (2) the mantle has a high capacity to retain water that otherwise would be available for stream flow.

In regard to the first point, it is shown in Figures 3, 4, 5, and 6 that even though considerable rain fell and snow melted after October each year, practically no increase in stream flow occurred (except for channel interception) until the moisture content of the mantle was raised to field capacity.

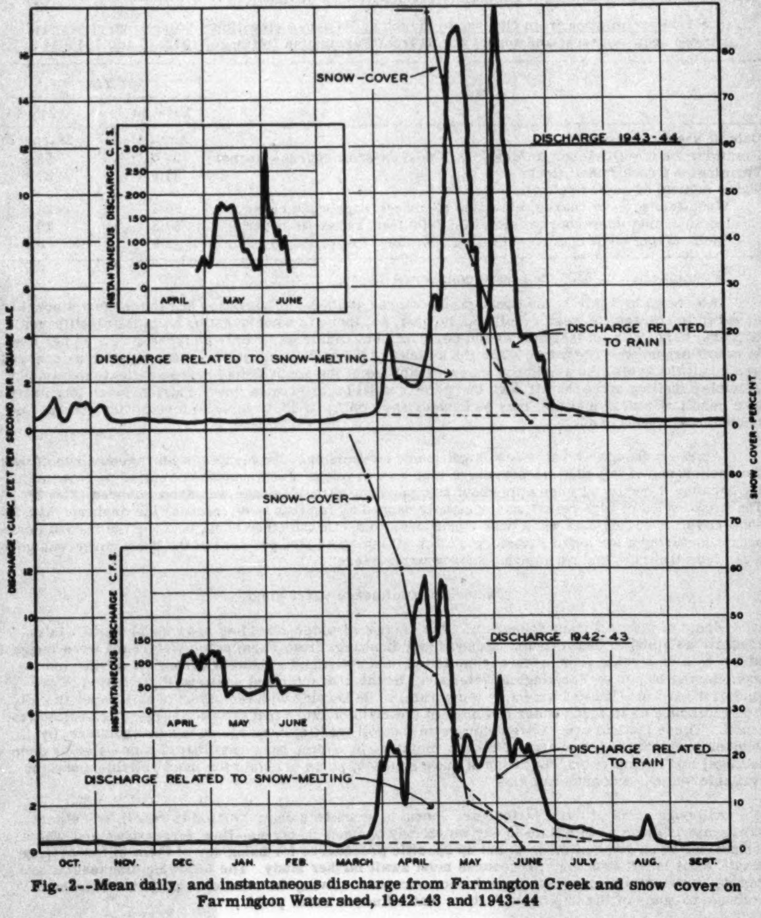

Fig. 2--Mean daily and instantaneous discharge from Farmington Creek and snow cover on Farmington Watershed, 1942-43 and 1943-44

The same charts show also the high water-holding capacity of the two mantles; that in the six-foot north-facing mantle was 22 inches of water, of which about 14 inches was removed by evaporation and transpiration each summer (Figs. 3 and 5). In the south-facing mantle the capacity was 17 inches of water, of which about 11 inches was removed each summer (Figs. 4 and 6). These annual losses of water from the mantle due to evaporation and transpiration are roughly half of the normal precipitation at the site from October 1 to March 31.

In addition to the moisture that was removed each year by transpiration and evaporation the south-facing mantle contained about five inches of water and the north-facing mantle about eight inches at the end of September.

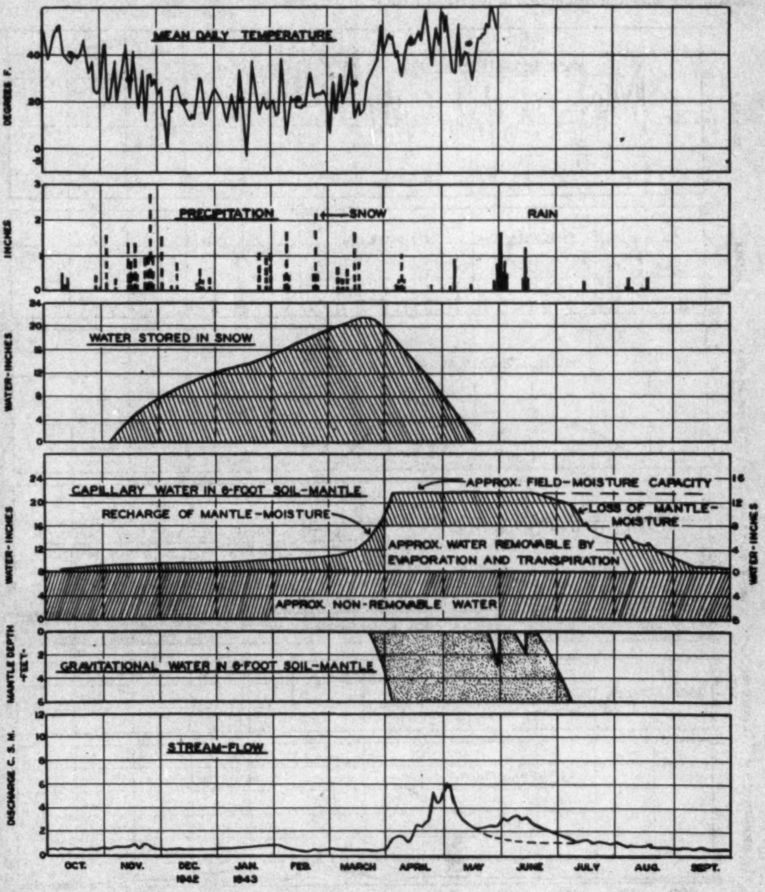

Fig. 3--Relation of stream flow to temperature, precipitation, snow storage and melting, and to soil moisture and gravitational water, Miller Drainage, 1942-43

Although the south-facing mantle was at field capacity (17 inches) when snow surveys were made in both years, the moisture in the north-facing mantle, which has a capacity of 22 inches, was only ten inches in 1943 (April 1) and nine inches in 1944 (March 25). It is commonly known, however, that the soil beneath the snow may be relatively dry on April 1, showing great fluctuation in moisture content of the mantle from year to year.

After the moisture content of the soil mantles was raised to field capacity, water continued to enter the soil as melting ensued, moving through under the pull of gravity. The period during which gravitational water was present in each mantle corresponds very closely with the period of high runoff in spring from the respective north- and south-facing drainages. These same relationships are shown also by studies on the Wasatch Plateau in central Utah [CROFT and MARSTON, 1943] and in the Wasatch Mountains of northern Utah [CROFT, 1944 a].

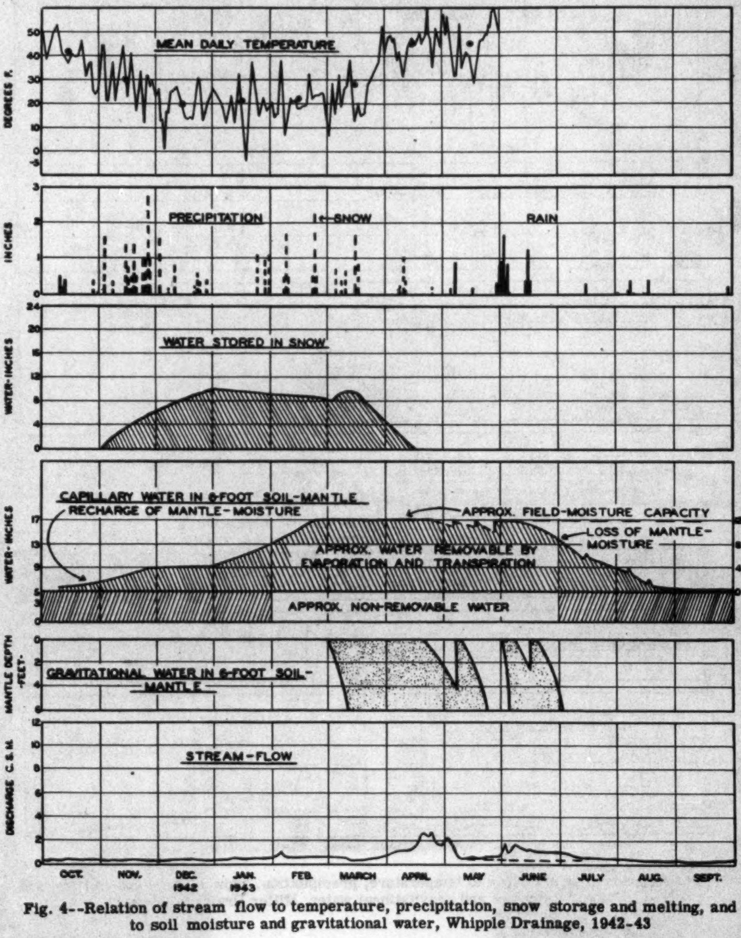

Fig. 4--Relation of stream flow to temperature, precipitation, snow storage and melting, and to soil moisture and gravitational water, Whipple Drainage, 1942-43

At all observation points the infiltration capacity of the soil was greater than the rate of melting, and no surface runoff occurred. The highest recorded melting rates at 8700-foot elevation on the Wasatch Plateau in April-June 1942 were 0.20 inch of water per hour and 1.97 inches per day [CROFT, 1944 b]. In the Farmington Drainage at 9000-foot elevation on July 29, 1942, measured rates were 0.40 inch and 3.5 inches, respectively. Known infiltration capacities of soil in both drainages are considerably in excess of these snow-melting rates.

Surface runoff does occur sometimes, when the mantle becomes completely saturated as a result of long periods of rapid melting of snow. This seems, however, to be the exception and not the general rule.

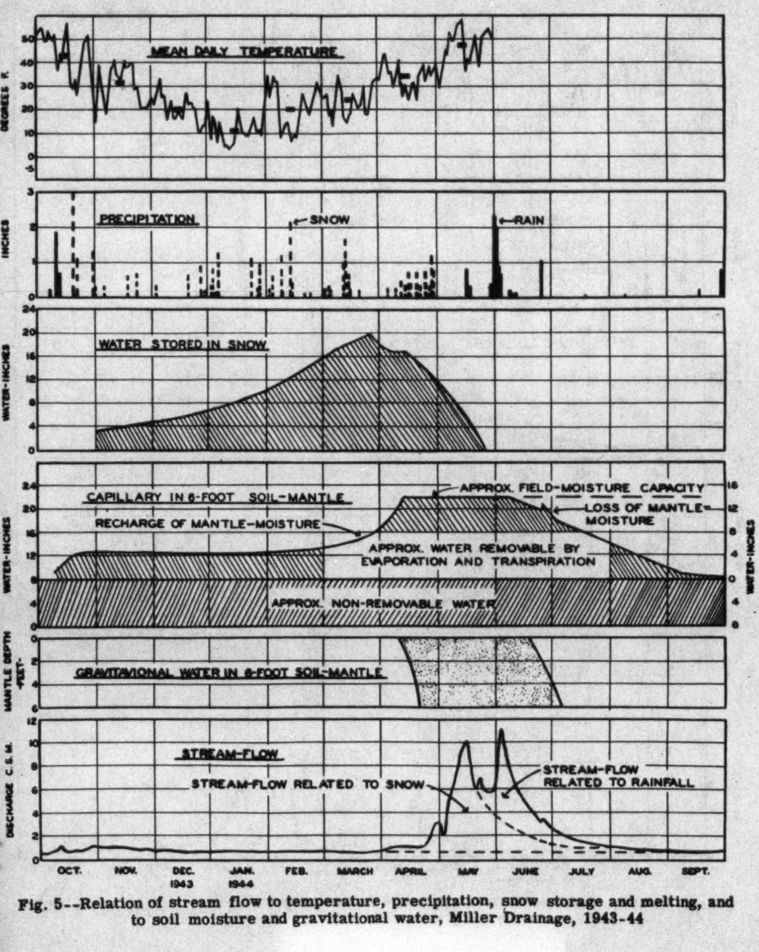

Fig. 5--Relation of stream flow to temperature, precipitation, snow storage and melting, and to soil moisture and gravitational water, Miller Drainage, 1943-44

As stated by CLYDE [1940] and CLYDE and WORK [1943] "Runoff is a residual and equals the difference between the total precipitation on, and the loss from, a given watershed." The major loss of water from the Farmington Watershed was that which entered the mantle each year only to be retained there by capillarity and later lost by evaporation and transpiration. The residual part of the precipitation is largely that which passed through the mantle as gravitational water and consequently became available for stream flow. Obviously the greater the capacity of a mantle to hold capillary water the smaller will be the amount of water available for stream flow from equal amounts of precipitation. Accordingly, a mantle in early spring with a capillary moisture deficit of ten inches of water, overlain by snow with a water content of ten inches will yield no water to stream

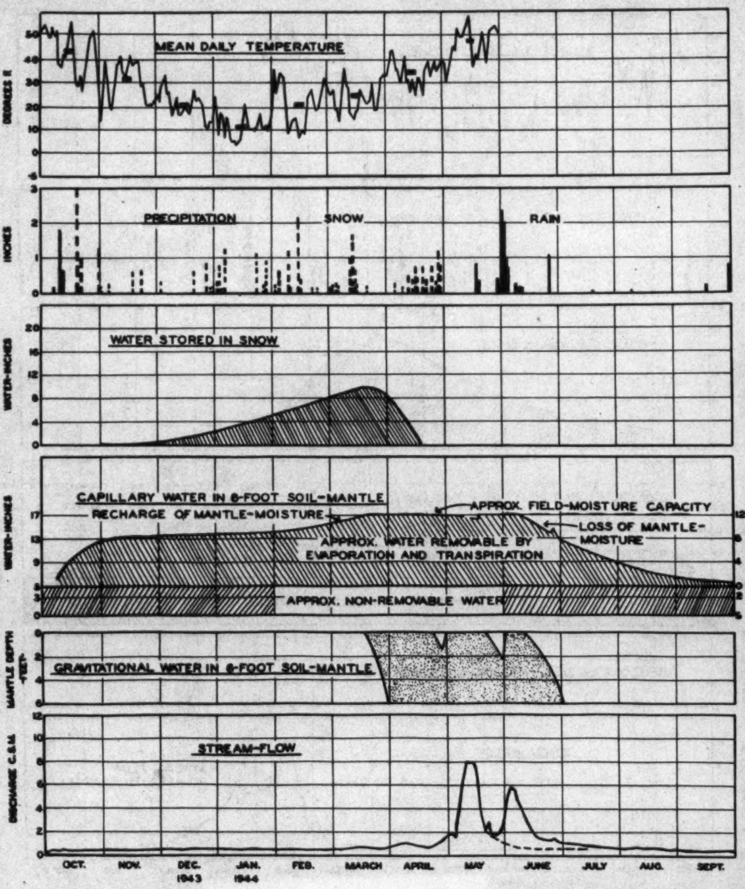

Fig. 6--Relation of stream flow to temperature, precipitation, snow storage and melting, and to soil moisture and gravitational water, Whipple Drainage, 1943-44 flow. On the other hand the same mantle, if its moisture content is at field capacity, will yield almost ten inches of water when overlain by snow with water content of ten inches.

This relation of available water and water-holding capacity of the mantle to stream flow suggests also an important reason why some drainages yield no runoff and why others yield little if any runoff from their lower parts. In the Intermountain Region drainages without streams, in most instances, do not exceed 7500-foot elevation, and in general water stored as snow on April 1 probably does not exceed the capillary moisture deficit of the mantle. As a result there is no "residual" water available to generate stream flow. The same condition exists on the lower portion of practically all drainages with permanent streams. Soil mantles in the upper portions of a drainage are seldom able to retain in capillary form, or to support sufficient vegetation, to consume all the water stored as snow, so that there is usually a "residual" amount available to generate stream flow. In general, on Wasatch Mountain Watersheds, this transition from a non-water-yielding to a water-yielding zone occurs somewhere between 6500- and 7500-foot elevation.

It is quite obvious that on drainages such as Farmington the capacity of the soil mantle to store water in capillary form that is not available for stream flow, and fluctuation in the amount stored each year at the time snow surveys are made, may be an important factor in making reliable water-supply forecasts. Mantle moisture is of sufficient significance in water-supply forecasting to justify careful additional study.

Recharge of mantle moisture by October precipitation--In view of the fact that moisture content of the mantle must be raised to field capacity each year before appreciable spring runoff can occur, precipitation that contributes to this should be included in the estimate of water supply. As Figures 3, 4, 5, and 6 show, September was the month of lowest content of mantle moisture, and recharge of both soil mantles with capillary water began near the first of October in 1942 and 1943. This changeover, from loss of mantle moisture in September to recharge in October, coincides quite closely with the elimination of transpiration by leaf-fall and a general increase in precipitation.

October precipitation in 1943 (8.3 inches), the year of high runoff, was five times as great as in 1942 (1.6 inches), the year of low runoff. Although about half of the precipitation during October 1943 came as snow, it melted completely from the south- and partly from north-facing slopes before winter storage began.

Soil-moisture recharge, as a result of this precipitation in October was about 1.2 inches in both soil mantles in 1942. The remaining 0.4 inch was probably lost through interception and evaporation and in a small way by transpiration. In 1943 recharge was seven inches on the south-facing site, where all snow melted, and four inches on north-facing site where about three inches of water was stored as snow at the end of October.

Amount of water lost by evaporation from soil or from snow in early fall is now known. Snow-evaporation studies on the Wasatch Plateau in April and May 1942 gave evaporation rates varying from 0.005 inch (of water) to 0.07 inch daily depending on vapor-pressure differences between snow and air [CROFT, 1944 c].

These figures indicate that, at the sites studied, recharge of the mantle moisture by precipitation before snow begins to accumulate varied greatly from year to year. Such recharge cannot be evaluated by snow measurements in spring alone, and therefore precipitation during October is a factor that should be given consideration in forecasting runoff.

Recharge of mantle moisture by winter snow melting--Another factor that cannot be evaluated by snow measurements in spring is the amount of water that enters the soil mantle as a result of melting of snow in winter. During the period of snow accumulation from November to March, considerable water was released to the soil mantle by melting snow, although the amount and rates varied considerably at the two sites. Following is a summary of mantle recharge from melting snow at the north- and south-facing sites from November 1 to the time field capacity was attained, compiled from Figures 3, 4, 5, and 6.

Water year	1942-43		1943-44	
North- or south-facing slope	North	South	North	South
Date recharge started	Dec. 30, 1942	Nov. 1, 1942	Jan. 30, 1944	Nov. 1, 1943
Date field capacity reached	Apr. 3, 1943	Feb. 25, 1943	Apr. 12, 1944	Mar. 20, 1944
Number of days required	94	117	73	141

Amount of recharge (inches)	12.0	10.4	9.5	4.0
Mantle moisture-deficit on snow-survey date	4.0	0.0	5.0	0.0
Number of days, before (+) or after (-) snow survey that mantle reached field capacity	-3	+35	-18	+5

At the south-facing site, where solar insolation is relatively high, some recharge took place all winter with fairly rapid recharge beginning in January 1943 and in February 1944. As a result, the mantle at this site was at field-moisture capacity 35 days prior to the date of snow survey in 1943 (April 1) and five days in advance of this date (March 25) in 1944. On the other hand, at the north-facing site where solar insolation is relatively low, winter recharge followed a much different pattern. Here recharge was very slow from November through February in both years but very rapid during March 1943 and during March and early April 1944. At this site field capacity was attained about three days after the snow survey in 1943 and about 18 days after in 1944.

The considerable amount of snow water that entered both north- and south-facing mantles at the 7000-foot station in the Farmington Drainage doubtless has a marked effect on runoff that cannot be evaluated by snow measurements alone. Although no measurements of soil moisture were made at the high 8300-foot station it is probable that winter melting occurred here also, because solar insolation is relatively high and the snow surface is exposed to direct sunshine.

A solution to this problem, which is discussed later, probably may be found by locating snow courses at sites where winter melting is negligible.

Loss of water by deep seepage--The fact that the average two-year runoff from north-facing Miller Drainage was 66 per cent higher than that from south-facing Whipple Drainage raises the question as to the cause (Table 2). The annual precipitation on the two drainages is about the same so that the difference cannot be attributed to this factor. Because Miller Drainage, the high-yielding one, has more luxuriant vegetation than Whipple Drainage, it does not seem reasonable to ascribe the difference to either interception of rainfall or transpiration by vegetation.

Table 2--Total runoff compared to runoff caused by rainfall between May 15 and June 15, 1942-43 and 1943-44

Drainage	Runoff		
	Total annual	May-June	
	inch	inch	pct total
		1942-43 (Precipitation 7.3 inches)	
Farmington	23.9	5.0	21
Miller	16.7	2.2	13
Whipple	10.1	0.7	7
		1943-44 (Precipitation 7.9 inches)	
Farmington	27.6	6.4	23
Miller	23.9	3.6	15
Whipple	14.5	2.6	18

Although only a suggestive answer can be given to this question, a comparison of the periods of high runoff from each drainage with the periods of mantle gravitational water may give a clue. On Whipple Drainage, as shown in Figures 4 and 6, gravitational water appeared in the mantle about 30 days before marked increase in stream flow occurred. During this time melting was slow and it is possible that the infiltration capacity of the underlying bedrock was high enough to permit considerable water to enter aquifers in the rock. Outlet for such water, if any, is probably below the stream channel and possibly completely off the watershed.

On Miller Drainage snow melting was delayed, as a result of low solar insolation and protection afforded by timber, until the arrival of relatively warm weather when melting progressed rapidly. In consequence, as is shown by Figures 3 and 5, mantle moisture was raised to field capacity at a relatively rapid rate and, soon thereafter, gravitational water appeared in the mantle and stream flow increased. It seems reasonable to assume that under these conditions a much smaller proportion of the available gravitational water enters aquifers in bedrock than when melting is prolonged.

These conditions suggest a tentative generalization, namely, that from the same amount of snow, rapid melting will result in greater water yield to streams than slow melting, even though no surface runoff occurs.

Spring rain--Rainfall from April 1 to May 15, while snow was melting and from May 15 to June 15, after most of the snow was gone caused considerable runoff in both years. In fact the rains during May to June, most of which occurred during the week May 28 to June 3, caused a second period of high runoff that was isolated as shown in Figure 2 and the amount determined.

These rains during May to June, which amounted to 7.3 inches in 1943 and 7.9 inches in 1944, are quite unusual in the Intermountain Region, but their occurrence and the resultant runoff from Farmington Drainage emphasize the extent to which rainfall can cause runoff. As shown in Table 2 these rains were responsible for 21 per cent in 1942-43 and 23 per cent in 1943-44 of the total runoff.

In view of this high runoff from the rains during May to June it is reasonable to assume that the proportion of runoff from rains during April to May, while much of the watershed was snow covered, was even higher. If runoff caused by the rains during April to May (2.8 inches in 1943 and 6.3 inches in 1944) is calculated using the percentages of runoff obtained for the rains during May to June, it is shown that not less than eight per cent of runoff in 1942-43 and 18 per cent in 1943-44 resulted from rains during April to May. In all probability the percentages were actually higher in view of the high moisture content of the mantle in April and May.

The data show also that moisture content of the soil mantle has a marked influence on the amount of runoff from rainfall. On June 26, 1944, when the mantle had begun to dry out, one inch of rain caused no runoff, except for channel interception, because all of the rain was retained by the mantle as capillary water.

The influence of mantle moisture on runoff from rain is shown also by comparing runoff from drainages with relatively dry and relatively wet soil mantles. As shown in Table 2, runoff from south-facing Whipple Tributary was seven per cent of the total annual yield in 1942-43 and 18 per cent in 1943-44. When the bulk of the rains during May to June came in 1943, most of the drainage had been free of snow for about five weeks, no gravitational water was in the mantle, and capillary moisture was about two inches below field capacity (Figure 4). The next year, however, there was more capillary and gravitational water in the mantle (Figure 6) and, accordingly, a larger amount of precipitation went through the mantle to generate stream flow than in 1943.

These same rains during May to June provided a means also of comparing runoff from spring rains with that of precipitation from October to March. In showing these relationships, runoff above prime flow which is related to the snow-melting period is compared with runoff above prime flow which is related to rainfall (Figure 2). The comparative data for runoff are shown in Table 3. Since the precipitation used in making these comparisons is that measured at 7000 feet rather than a mean for the entire drainage basin, the values in Table 3 are considered as indices of runoff only.

Considering Farmington Drainage for the year 1942-43, the year of low runoff, the runoff index related to precipitation in October to March is 51 and that related to rains in May to June is 68. The following year the respective indices are 60 and 80. The index for May to June is 33 per cent higher in both years than that for October to March. The indices for runoff during May to June for Miller and Whipple drainages are considerably higher both years than those for October to March. This is doubtless due to the fact that a large proportion of the precipitation in October to March was retained by the mantle as capillary water because of its very dry condition on October 1. In the spring, however, the mantle was wet so that it retained a smaller proportion of the rain than during October to March.

There is little doubt that rainfall in spring influences greatly the yield of water from Farmington Watershed, not only because the amount varies greatly from year to year but because its effectiveness in producing runoff is greatly influenced by the moisture content of the soil mantle.

Location of snow courses

The discussion thus far has emphasized that recharge of soil-mantle moisture by rain in early fall and melting snow during the winter that contribute water to the mantle and to deep aquifers are among the major factors that make the water content of the snowpack on April 1 a questionable index of available water supply. Actually a snow-course measurement may be considered as a substitute for measurements of the total amount of water that falls on a watershed during fall and winter. The question naturally arises, then, as to whether some locations are better for this purpose than others and what the characteristics of the most desirable locations are? Data from Farmington Drainage provide a basis for making some suggestions along this line.

Table 3--Runoff above prime flow and precipitation, October 1-March 31, April 1-May 15, and May 15-June 15, 1942-43 and 1943-44

Drainage	Period						
	Oct. 1-Mar. 31			Apr. 1-May 15	May 15-June 15		
	Precip. index[a]	Runoff		Precip.	Precip. index	Runoff	
	inch	inch	pct precip.	inch	inch	inch	pct precip.
				1942-1943			
Farmington	27.7	14.1	51	2.8	7.3	5.0	68
Miller	27.7	6.7	24	2.8	7.3	2.2	30
Whipple	27.7	2.2	8	2.8	7.3	0.7	10
				1943-44			
Farmington	25.9	15.5	60	6.3	7.9	6.3	80
Miller	25.9	10.0	39	6.3	7.9	3.6	46
Whipple	25.9	4.9	19	6.3	7.9	2.6	33

[a] Measured in Farmington Canyon at 7000-foot elevation.

As shown in Table 1, at the two 7000-foot snow courses the amount of snow in storage when surveys were made each year varied greatly even though the amount of snow that fell on each was the same. In 1943 the water content of snow at the north-facing course was about five times that at the nearby south-facing course, and in 1944 it was more than twice as much. The difference is obviously due to more melting at the south- than at the north-facing course.

This difference in melting of snow at the two sites is no doubt a result of local difference of temperature brought about by two factors, namely, solar radiation and vegetal cover. For example, the north-facing site receives much less solar heat per unit area than the south-facing site because of a difference in exposure of the two surfaces to the Sun's rays. In addition, snow at the south-facing site is exposed to the direct rays of the Sun, whereas that at the north-facing site is shaded by an aspen-fir cover.

Most of the snow courses in use at the present time are sufficiently long to include what are believed to be average conditions of slope, aspect, and vegetal cover. Doubtless there is considerable melting of snow on the parts of such courses where solar insolation is high and where the snow surface is exposed to direct sunshine. Since snow courses are established for the purpose of providing an index of the amount of water available for runoff, locations should be best where the amount of snow in storage is affected least by winter melting.

The most desirable site is one that will function as a natural storage precipitation gage. A small pocket in timber cover on a slope where solar insolation is relatively low and where the soil is deep enough to retain all moisture from rainfall in October and winter snow-melt would probably be best. Such a site would doubtless retain in storage a high percentage of winter snowfall. In addition, water from snow that melted during the winter and from rains in early fall would be stored in the soil mantle where it also could be measured.

An inventory of available water at such a site would include the water content of the soil mantle in addition to that of the snowpack. There is substantial evidence for believing that estimates of available water made in this manner would provide a sounder basis than snow alone in forecasting runoff.

Summary and conclusions

This study indicates some of the important factors in addition to the water content of the snowpack on April 1 that are related to water yield from Farmington Watershed. Inasmuch as many of the high water-yielding lands in the Intermountain Region have the same general characteristics the following summary of results, and the conclusions, apply also in a general way to these lands.

Watershed soil mantles have high capacities for capillary water that must be recharged each year before water can pass through under the force of gravity to generate stream flow. Since the capillary moisture deficit of the mantle on April 1 may vary from almost nothing to a high percentage of the water in the snowpack, a knowledge of mantle-moisture content is necessary if accurate estimates of the water available for stream flow are to be made.

The soil mantle has the lowest water content about the last of September each year and, therefore, runoff the following year is influenced by increases in soil moisture after that time. During October mantle moisture increased at the location studied as much as 25 per cent of the annual runoff. This occurred as a result of rain, and snow that melted, neither of which were evaluated by measurements on April 1 of the snowpack. Thus, the extent of recharge in October may account for error in stream-flow forecasting unless it is considered in estimating the available water supply.

Winter melting of snow may result in transfer of substantial amounts of water from the snow pack to the soil mantle where it cannot be evaluated unless the moisture content of the soil mantle is measured, thus introducing an additional source of error in forecasting water supply based only on the snowpack on April 1. The water content of the snowpack on April 1 on a south-facing slope without timber cover, was at times only 20 per cent of the precipitation during October to March, whereas that on a nearby north-facing slope in timber at the same elevation (7000 feet) was as high as 80 per cent of the precipitation during October to March.

The accuracy of stream-flow forecasts based alone on the snowpack on April 1 can doubtless be improved by sampling snow at sites where a minimum of snow melting occurs during the winter. This is because a more reliable index of available water may be had at such sites than at sites where the amount of snow in storage on April 1 may depend as much, or more, on winter melting as on total snowfall.

A reliable index of available water may be obtained by measuring water stored in the soil mantle in addition to that stored as snow about April 1. The ideal site to obtain these two measurements would be in small open pockets in timber cover where solar insolation is low and where there is a soil mantle four to six feet deep. Such a site would function as a natural storage precipitation gage because it would provide, either as snow or soil moisture, a fairly reliable index of the available water supply.

Soil-moisture sampling pits used in this study provided a means of obtaining moisture content of the soil mantle at any time of year by direct measurement of soil samples. For purposes of forecasting stream flow, however, studies should be made at higher elevations of some of the indirect methods of measuring soil moisture that have given reliable results under field conditions at valley stations.

In addition to capillary water that enters the mantle, only to be removed by evaporation and transpiration, probably more water passes through the mantle into bedrock below stream channels during prolonged periods of winter snow melting than when the snow pack melts rapidly. These phenomena, which are probably very closely related to conditions of temperature, apparently influence both seasonal distribution of stream flow and total runoff.

Rain which falls after measurement of the snowpack on April 1 may account for as much as 40 per cent of the total runoff. Precipitation in April while snow is melting is more efficient in producing runoff than equal amounts of the precipitation during October to March because very little of the rainfall in April is retained by the mantle whereas much of that from October to March is retained in the mantle as capillary water. Furthermore, rainfall immediately after snow melting, while the soil mantle is wet, may also yield high runoff. When such post-snow-survey precipitation occurs it may cause runoff considerably in excess of even the best possible forecasts.

Rainfall is not effective in producing stream flow, except as channel interception, after the soil mantle attains a definite capillary moisture deficit near the surface.

Peak discharge from rainfall may be higher than that from snow melting; mean daily discharge from rain exceeded that from melting snow and instantaneous discharge occurred from rainfall that was twice as high as that from melting snow.

The watershed area covered with snow when peak runoff occurred varied greatly--on south-facing slopes it was only ten per cent, on north-facing slopes 75 per cent, and on the entire watershed 40 per cent.

As detailed studies reveal more information concerning the factors that influence the recharge of mountain lands with water each year, and the factors that influence the amount that may be released from them as stream flow, more accurate methods of forecasting stream flow will no doubt be developed.

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A NEW FORECASTING CURVE FOR THE KAWEAH

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Abstract--This paper expresses the April-through-July runoff volume of the Kaweah River at Three Rivers as a function of water equivalent of snow on the ground April 1, spring precipitation, and soil-moisture deficiency in the fall. The empirical relation obtained from 15 years of record has a maximum error of less than ten per cent. The novel feature of the soil-moisture deficiency factor is that it is determined by fall precipitation prior to the accumulation of continuous snow cover at a particular station.

Introduction--Although this short paper deals with the details of the construction of a new forecasting curve for the Kaweah River, no new principles are involved. It is, however, a case where some of the old principles have fitted together with pleasing results.

This paper might be considered as a member of the group of papers presented at the meeting of the Snow Conference in Spokane six years ago, and published in the American Geophysical Union Transactions under the general title "The effect of soil priming by fall precipitation on spring runoff" [SYMPOSIUM, 1939].

Forecasts of runoff for California streams have in the past been based on but two factors, namely, measured snowpack and precipitation during the runoff period [PAGET, 1938; ELGES, 1939]. This method of analysis has proved to be unsatisfactory for the Kaweah Watershed. Because of the need this new curve was developed. This new curve includes a third factor, namely, the precipitation that falls on the watershed prior to the beginning of accumulation of snowpack, evaluated in terms of its soil-priming influence.

Speaking in general terms, it may be stated that during the summer months in the Sierra Nevada, evaporation and transpiration reduce the moisture in the soil cover below field capacity. Under normal conditions this soil-moisture deficiency must be replaced before there will be any runoff from a melting snowpack.

The soil-moisture deficiency may be entirely or only partially replaced by precipitation that falls prior to the accumulation of snow, but any deficiency that is not made up before the snow falls is apt to remain unsatisfied until the snow begins to melt in the spring of the year. Then the first demand upon water released by the melting snow will be to satisfy the remaining deficiency [CLYDE, 1940; BLANEY, 1930].

In practical forecasting, such as is practiced by the California Cooperative Snow Surveys, speed of gathering the data and a simple routine of computations are very important considerations. As finally worked out, the new curve for the Kaweah observes these considerations.

Three factors are used, namely, soil-moisture deficiency, snowpack water equivalent, and precipitation during the runoff period. These three definite factors are adopted boldly without quibbling over minor modifications.

Soil-moisture deficiency--The field capacity of a soil is defined as the amount of water it can retain against the downward pull of gravity. Evaporation and transpiration deplete this during the summer. It is assumed for the Kaweah Watershed that this annual depletion can be replaced by eight inches of precipitation as measured at Giant Forest more or less centrally located in the watershed.

This amount of eight inches, while open to controversy, works out well empirically and is also in line with some figures published for other areas by CHARLES H. LEE [1941], P. B. ROWE [1941], and by F. J. VEIHMEYER [1944].

The date each year on which the snow blanket began to accumulate in the Kaweah Watershed has been assumed to be the same date as for Huntington Lake a little farther north, figures for which have been supplied by the Southern California Edison Company, from the records kept there by their lake tender.

These dates are shown in Table 1. That Table shows for each year the amount of precipitation for Giant Forest between October 1 and the date the snow began to accumulate. The deficiency below eight inches is shown for each year in the last column. When the prepack precipitation is greater than eight inches, the excess is neglected, as going to ground water and draining out during the winter months.

Table 1--Computation of soil-moisture deficiency, Kaweah Watershed

Season (1)	Date snow accum. began[a] (2)	Precipitation at Giant Forest preceding snowpack					Deficit below eight inches (10)
		Oct. (3)	Nov. (4)	Dec. (5)	Jan. (6)	Total (7)	
		in	in	in	in	in	in
1929-30	Jan. 4	0.0	0.0	0.59	(0.0)	0.6	7.4
1930-31	Dec. 31	0.16	4.28	(0.0)	. . .	4.4	3.6
1931-32	Nov. 14	0.10	(0.0)	. . .	. . .	0.1	7.9
1932-33	Nov. 30	0.10	(0.19)	. . .	. . .	0.3	7.7
1933-34	Dec. 11	2.23	0.57	(0.41)	. . .	3.2	4.8
1934-35	Nov. 15	1.16	(1.14)	. . .	. . .	2.3	5.7
1935-36	Dec. 12	0.58	1.78	(0.49)	. . .	2.9	5.1
1936-37	Dec. 6	2.51	0.10	(0.0)	. . .	2.6	5.4
1937-38	Dec. 23	0.14	1.0	(16.28)	. . .	17.4	0.0
1938-39	Dec. 19	4.29	1.13	(0.57)	. . .	6.0	2.0
1939-40	Jan. 4	3.99	0.08	0.88	(0.0)	5.0	3.0
1940-41	Dec. 16	4.15	1.04	(0.36)	. . .	5.6	2.4
1941-42	Dec. 9	2.79	4.51	(2.82)	. . .	10.1	0.0
1942-43	Jan. 10	0.33	4.37	6.12	(0.0)	10.8	0.0
1943-44	Nov. 5	0.87	(0.0)	. . .	. . .	0.9	7.1

[a] At Huntington Lake,

Note: Figures shown in parentheses are for that part of month prior to date shown in Column (2).

Snowpack water equivalent--The snowpack water equivalent is found by taking a direct mean of the following four stations: Panther Meadow; Hockett Meadow; Quinn Ranger Station; and Big Meadows. The water equivalent as of April 1 for each snow course is shown in Table 2 together with the yearly means.

Table 2--Water equivalent of snowpack on April 1, Kaweah Watershed

Year	Panther Meadow	Hockett Meadow	Quinn Ranger Sta.	Big Meadows	Total of 4 courses	Mean of 4 courses
	in	in	in	in	in	in
1930	28.3	29.3	13.0	22.0	92.6	23.1
1931	16.0	15.1	6.7	15.2	53.0	13.3
1932	52.0	42.8	30.9	43.9	169.6	42.4
1933	35.7	30.0	22.7	29.0	117.4	29.4
1934	22.4	19.0	5.8	14.6	61.8	15.4
1935	32.2	24.0	21.5	24.0	101.7	25.4
1936	50.8	44.2	30.0	36.8	161.8	40.4
1937	62.9	48.1	31.8	46.4	189.2	47.3
1938	56.9	42.4	36.8	44.7	180.8	45.2
1939	27.2	20.3	14.5	13.2	75.2	18.8
1940	44.1	43.4	29.8	31.5	148.8	37.2
1941	48.8	48.5	40.0	39.9	177.2	44.3
1942	42.4	36.1	23.5	32.0	134.0	33.5
1943	52.4	40.3	32.0	31.6	156.3	39.1
1944	35.2	28.1	21.9	25.1	110.3	27.6

In analyzing the conformity of each snow course with the general situation each year, a comparison diagram, such as Figure 1, is helpful. For each year, the snowpack runoff is plotted to

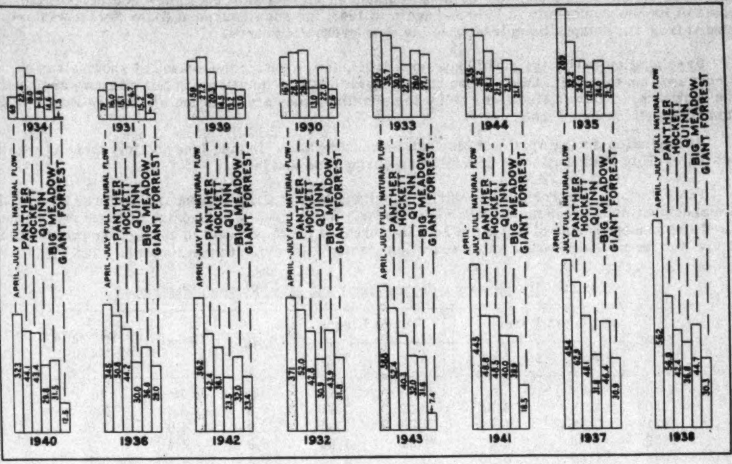

Fig. 1 -- Comparison diagram, Kaweah at Three Rivers, 1930-44

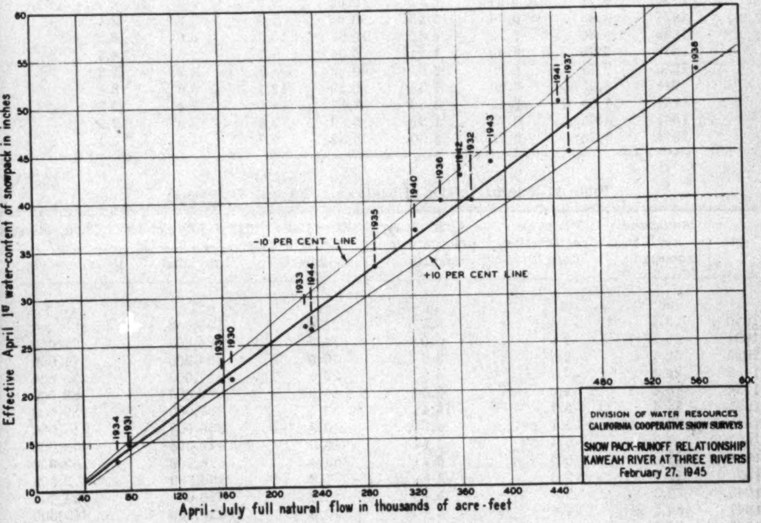

Fig. 2 -- Snowpack runoff relationship, Kaweah River at Three Rivers, 1930-44

some convenient scale alongside the water content as measured at each snow course. On the basis of its non-conformity in 1940 and again in 1943, the snow course at Giant Forest was excluded from the computations leading to the new forecasting curve.

Precipitation during the runoff season--Precipitation during the season of snowmelt is a direct addition to runoff. Often at the higher elevations precipitation will fall as snow, augmenting the snowpack. At lower elevations below the snowline, such precipitation will fall as rain with an immediate effect upon runoff.

Precipitation during April and May can be considerable. During June and July there is usually but little. This study neglected precipitation during June and July.

Table 3 shows the precipitation during April and May at Giant Forest and at Three Rivers, the two precipitation stations maintained in the Kaweah Watershed. The average at these two stations for the combined months of April and May is increased by 25 per cent to convert the precipitation figure into terms of snowpack water equivalent having a like effect upon runoff [ELGES, 1939].

Table 3--Precipitation during April and May, Kaweah Watershed

Year	Giant Forest		Three Rivers		Total	Mean	125 per cent of mcan
	Apr.	May	Apr.	May			
	in	in	in	in	in	in	in
1930	2.14	4.38	1.07	1.73	9.3	4.6	5.7
1931	2.57	1.89	2.35	1.05	7.9	4.0	5.0
1932	3.68	1.93	1.38	1.88	8.9	4.4	5.5
1933	1.69	4.09	0.57	1.91	8.3	4.1	5.1
1934	0.00	2.64	0.00	1.05	3.7	1.8	2.3
1935	13.34	2.02	6.03	0.13	21.5	10.7	13.4
1936	4.18	0.84	2.12	0.64	7.8	3.9	4.9
1937	3.45	0.04	1.53	0.00	5.0	2.5	3.1
1938	6.80	1.23	4.68	0.51	13.2	6.6	8.2
1939	2.26	2.09	1.91	0.81	7.1	3.6	4.5
1940	2.37	0.00	2.01	0.08	4.5	2.2	2.7
1941	6.98	0.40	5.56	0.15	13.1	6.6	8.4
1942	7.63	2.47	3.58	1.17	14.9	7.4	9.2
1943	4.68	0.74	1.39	0.99	7.8	3.9	4.9
1944	5.20	0.69	3.00	0.82	9.7	4.9	6.1

Table 4--Summarization of basic data, Kaweah Watershed

Year	Measured April 1 snowpack	Prepack precipitation deficit	April-May precipitation addition	Effective April 1 snowpack	April-July runoff at Three Rivers	
					Computed	Observed
	in	in	in	in	a - f	a - f
1930	23.1	-7.4	5.7	21.4	158,000	167,000
1931	13.3	-3.6	5.0	14.7	84,000	79,000
1932	42.4	-7.9	5.5	40.0	364,000	371,000
1933	29.4	-7.7	5.1	26.8	217,000	230,000
1934	15.4	-4.8	2.3	12.9	64,000	69,000
1935	25.4	-5.7	13.4	33.1	287,000	289,000
1936	40.4	-5.1	4.9	40.2	366,000	345,000
1937	47.3	-5.4	3.1	45.0	420,000	454,000
1938	45.2	0.0	8.2	53.4	514,000	562,000
1939	18.8	-2.0	4.5	21.3	156,000	159,000
1940	37.2	-3.0	2.7	36.9	320,000	323,000
1941	44.3	-2.4	8.4	50.3	480,000	445,000
1942	33.5	0.0	9.2	42.7	394,000	362,000
1943	39.1	0.0	4.9	44.0	410,000	388,000
1944	27.6	-7.1	6.1	26.6	215,000	235,000

The forecasting curve--Table 4 shows a summary of the three factors derived in Tables 1, 2, and 3. The algebraic sums of the three factors shown in column (5) are the ordinates of the snowpack--runoff relationship curve. The runoff figures as measured at Three Rivers by the United States Geological Survey and shown in the last column of Table 4 are the corresponding abscissas.

The new snowpack--runoff relationship curve is shown in Figure 2. All points fall within ten per cent of the mean relationship line.

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DISCUSSION

W. B. LANGBEIN (U. S. Geological Survey, Washington, D. C., April 13, 1946)--Reduced to basic terms, PAGET correlates the runoff of Kaweah River during April to July with the following: (1) Pre-snow precipitation at Giant Forest; (2) average of snow cover in inches of water content on April 1 as measured at four stipulated snow courses; and (3) average precipitation during April to May at Giant Forest and Three Rivers.

PAGET sets up a formula for computing the effect of the pre-snow precipitation, on the theory that it determines the soil-moisture deficiency at the beginning of the snow cover. However, subtracting a deficiency is algebraically the same as adding the quantity directly. Thus, his formula is

$$\text{Runoff during April to July} = K\left[-(8 - P_A) + S + 1.25P_S\right] + C$$

where P_A is antecedent or pre-snow precipitation, S is snow on April 1, and P_S is precipitation during April and May at Three Rivers and Giant Forest. K and C are constants defining, respectively, the slope and intercept of the graph. It is specified that $(8 - P_A)$ cannot be less than zero. The above equation is equivalent to

$$K\left[P_A + S + 1.25P_S\right] + C'$$

where all quantities are the same as above except C′, which is a constant equal to (C - 8K).

It is not clear why PAGET used the record at Giant Forest alone for antecedent precipitation, but averaged records at Giant Forest and Three Rivers for precipitation during April and May.

The writer made inquiry into the validity of the postulated coefficients of P_A and P_S by graphical correlation methods explained by EZEKIEL [1941]. Graph (A) of Figure 1 shows the net variations in the supply ascribable to antecedent precipitation. Although there is considerable scatter, the points define a line with a slope of about 60 per cent. So far as the graph indicates

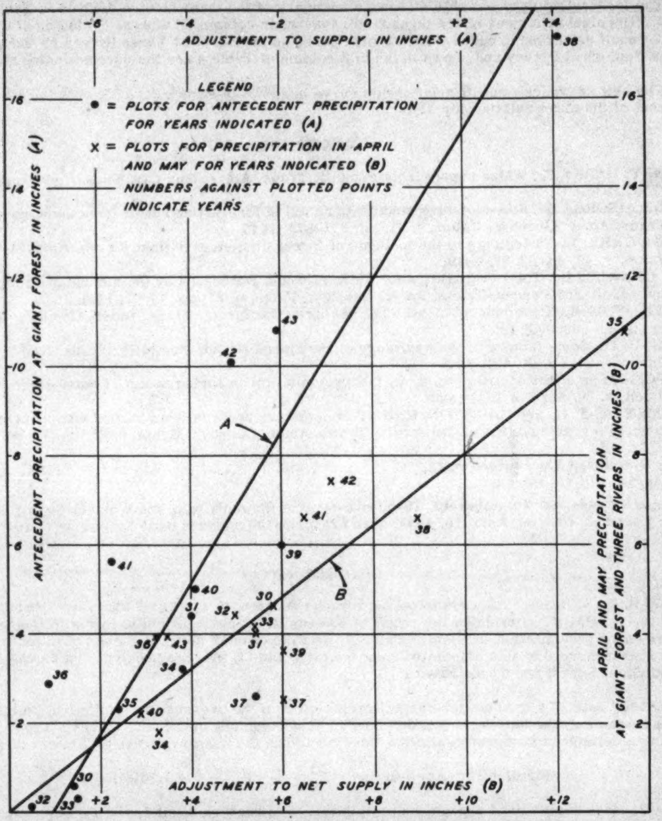

Fig. 1--Study of effect on net supply of (A) antecedent precipitation and (B) precipitation during April and May

there is no reason for terminating it at eight inches. PAGET'S treatment is equivalent to a line of 1:1 slope from the point - 8,0 to the point 0,8. For higher ordinates the zero abscissa was assumed to govern. Such treatment ignores the point for 1938 and in general does not appear to conform to the plotted points as well as to the line shown.

Graph (B) of Figure 1 shows a study of the variation in net supply ascribable to precipitation during April and May as measured at Giant Forest and Three Rivers. The plotted points confirm rather well the coefficient of 1.25 used by PAGET.

Figure 2 shows a plotting of total supply as computed by the formula $(0.6P_A + S + 1.25P_S)$ against April to July runoff.

The standard error of estimate is 5.1 per cent as compared with 7.2 per cent on PAGET'S graph. However, Figure 2 can only be adapted to forecast on April 1 provided precipitation during

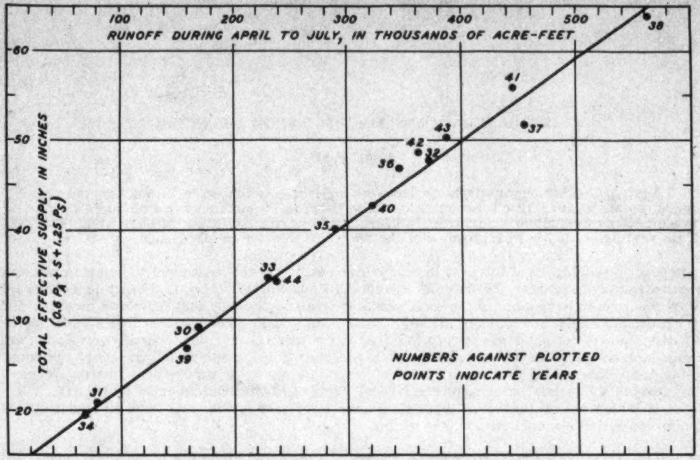

Fig. 2--Revised graph of seasonal runoff, Kaweah River at Three Rivers, California

April to May is assumed normal, say six inches. If this is done the standard error of forecast on April 1 is 16 per cent, with errors as high as 35 per cent in 1934 and 1935, owing largely to the unpredictability of spring rainfall.

If a slight tendency toward persistency in precipitation can be credited, then a graph should be prepared showing known effective supply as of April 1 as ordinate, and runoff during April to July as abscissa. In such a graph the precipitation during April and May would be presumed to vary as the known supply as of April 1. The best graphical fit indicates a standard error of forecast of 15 per cent.

A further suggestion for improvement might be to determine by statistical methods the weights to be given the several snow courses. It is possible that each should not be given equal weight as assumed.

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Transactions, American Geophysical Union Volume 27, Number III June 1946

MECHANIZED TRANSPORT FOR SNOW SURVEYING

R. A. Work

Abstract--This paper gives the reasons for increased interest in mechanized travel on snow, lists 12 characteristics to be noted in the performance of such a machine, and describes a series of field tests of a particular make of snow vehicle. This vehicle, which is described, met the requirements for performance.

Introduction--Magnified interest in mechanized snow-travel equipment is being shown by snow surveyors and cooperators. Three chief reasons account for this recent sharply increased interest: (1) Most young men have gone to the war, and long trips on snow by foot for older men are difficult; (2) increased demands for work of all sorts have been placed on cooperators with resulting pressure for completion of snow surveys in the shortest possible time; (3) recently developed military mechanized snow-travel equipment has been widely publicized. Snow surveyors, curious to know the facts, are asking that the Division of Irrigation, as snow survey coordinating agency, find or develop a low-cost, dependable means of lightweight mechanical snow transport. The Division of Irrigation is, therefore, making special efforts to locate, test, and/or encourage development of suitable machines for this purpose.

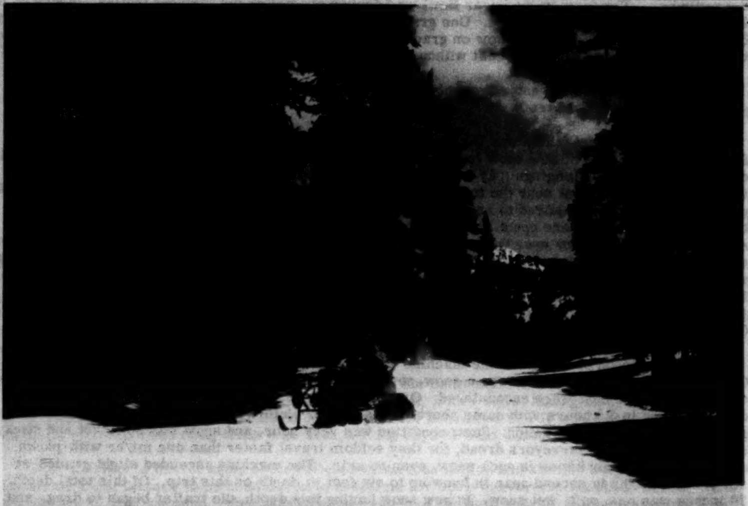
When the suitable machine or machines become known and available in quantity, funds with which to purchase them will become in part available from various sources, that is, irrigation districts, public and private utilities, counties, states, various Federal agencies, or other sources.

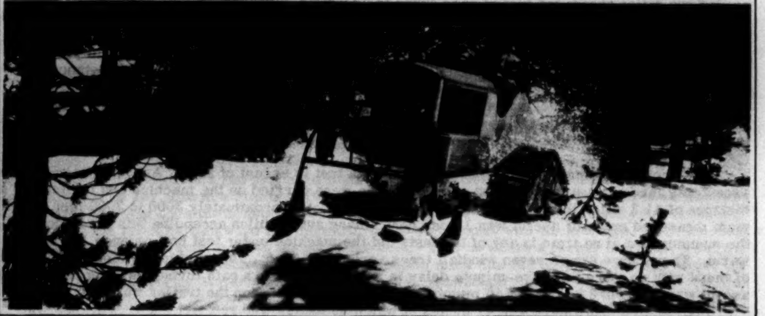
Several types of mechanized snow-travel equipment have been or are now being developed. All having promise are being tested under field conditions as rapidly as possible, to demonstrate their limitations before either extensive purchases are made or recommendations for purchase are furnished to other agencies.

Design of such machines will depend in part on terrain on which they are to operate. A universal purpose snow-survey machine must have incorporated in its design and performance the following characteristics: (1) Ability to travel on soft or sticky snow; (2) ability to ascend steep grades; (3) ability to traverse side slopes; (4) ability quickly to surmount obstacles such as fallen trees, rocks, and steep-banked channels; (5) ability to ford flowing streams; (6) ability to operate on snow-bare ground; (7) mechanical dependability; (8) portability; (9) maneuverability; (10) safety; (11) speed; and (12) economy of operation.

The purpose of this paper is to report to the Western Snow Conference results of tests of one of these machines which shows maximum promise of usefulness in snow-survey work.

Description of machine--The machine is supported on the snow at the rear by two oblong stainless-steel pontoons, each 72 inches long and 14 inches wide, one on each side of the chassis. Power from a six-cylinder automobile engine is applied through a four-speed transmission and truck differential to four sprocket gears, two in each pontoon, which engage and positively drive an open-link track on roller bearings endlessly around the supporting pontoons. The pontoons are independently mounted on the axle which enables the vehicle to better surmount obstacles. The machine is supported in front by two ingeniously connected hickory skis, each six inches wide and 72 inches long, which serve also to steer the machine. The steering gear is of cable construction, airplane type. On snow-bare ground small pneumatic-tired wheels may be quickly lowered to lift the skis from the ground. The overall length of the machine from tip of runner to rear of the pontoons is 182 inches. Braking is accomplished, if necessary, by means of a conventional emergency brake applied to the drive shaft. The cooling and ignition system is standard, the machine being equipped with radiator, generator, battery, self-starter, and lights. Gasoline-tank capacity is 40 gallons. The machine carries four people and is designed to haul trailers of different load capacities. Dry weight of the machine tested at Medford was 2270 pounds. The weight varies with the type of engine used. Top speed is about 20 mi/hr, but recommended operating speed is about ten mi/hr.





Figs. 1 and 2--Views of snow-survey transport

Field tests of machine--This machine was tested by a representative of the Division of Irrigation at Soda Springs, California, on January 10, 1945. The tests at Soda Springs were made on snow 30 to 40 inches in depth and for the most part of average density 30 per cent. The snow was of such structure and texture that a man on skis sank only two or three inches. The machine traveled several miles in a short time over this snow, towing a trailer loaded with 1600 pounds of steel, plus two passengers; the pay-load was about one ton. The machine crossed logs, open railroad tracks, steep-banked stream channels, and other obstacles, at speeds up to six to eight mi/hr in second gear. The consumption of gasoline on the round trip from Soda Springs to Sugar Bowl, a total distance of seven or eight miles, was about one gallon. High gear speeds of 12 to 15 mi/hr were reached on the return trip. The machine turned freely on open snow-fields in a radius of about 40 feet, but shorter turns were made by backing and filling. The machine handled quite well in a forest of lodge-pole pine without road or trail but would not operate, of course, in extremely dense timber. The snow in the Sugar Bowl was deeper and softer but, without trailer, grades up to 24 per cent were readily ascended. One grade of 34 per cent, over some down logs, was ascended, but the machine stalled in soft snow on grades exceeding 34 per cent. At Sugar Bowl, the machine traversed side slopes of 25 per cent without difficulty and without appreciable side slippage.

In March, 1945, the inventor brought one of his machines to Medford, Oregon, where it was given more difficult field tests.

On March 19 the machine was taken to Union Creek, near Medford, at an elevation of 3400 feet. About 20 inches of new snow (one to five days old) covered the ground there. Hauling a load of 11 men and their belongings (pay-load was 2000 pounds) the machine ascended a narrow, winding forest road to a point near the top of Huckleberry Mountain. Maximum grade of ascent was 15 per cent. Total time required to reach destination, six miles from Union Creek, was 50 minutes, but about ten minutes were spent in taking pictures en route. The machine climbed 1500 feet in six miles. Depth of snow near the mountain top was about 60 inches. The snow was only fair for skiing. A 190-pound man sank six inches on snowshoes. Performance of the machine in this test was as follows: Distance traveled, 12 mi; maximum grade ascent, 15 per cent; total ascent, 1500 feet; gasoline consumption, 6 gallons; oil consumption, none; total elapsed time round trip, 3 hr, 15 min; running time (estimated), 2 hr; average speed, 6 mi/hr; gasoline consumption per mile, 0.5 gallon; pay-load, 2000 pounds; gasoline consumption per ton-mile, 0.5 gallon.

In the afternoon of March 19 the machine was driven from end of the plowed road near Union Creek into Crater Lake Park, over a snow-covered paved road with broad right of way. No grades exceeding six per cent were encountered On this particular test the machine traveled 23 miles over the snow in 3.5 hours with some short delays to take pictures. Gasoline consumption was ten gallons, or 2.3 miles per gallon. Snow condition was very poor, and snow was soft, wet and sticky, of the sort that snow surveyors dread, for they seldom travel faster than one mi/hr with packs, often sinking to their knees in such snow, even on skis. The machine ascended slight grades at six to eight mi/hr in second gear in snow up to six feet in depth on this trip. Of this total depth, 36 inches was new, soft, wet snow. In new snow having this depth, the trailer began to drag, and speed of machine was reduced; so the trailer was released and four men on the machine alone proceeded two miles ahead, but turned back owing to oncoming darkness. It appeared on this trip that the skis supporting the front of the machine should be wider, perhaps ten inches wide for such soft snow. On hard or medium snow the present skis of six inches in width are suitable. Also, the inventor should wax his skis, as that would reduce the amount of power required to propel the machine and might increase its speed. Performance for this test was as follows: Distance traveled, 23 mi; maximum grade ascent, not over 6 per cent; total ascent, 2150 feet; gasoline consumption, 10 gallons; oil consumption, none; total elapsed time round trip, 3 hr 30 min; running time (estimated), 3 hr; average speed, 7.7 mi/hr; gasoline consumption per mile, 0.43 gallon; pay-load, 1600 pounds; gasoline consumption per ton-mile, 0.54 gallon.

On March 20 the machine was set against a hard test in ascent of Mount Ashland, Oregon. This ascent was made on a narrow forest road. Six men were carried on the machine and trailer. In a distance of 11.3 miles the machine climbed from elevation approximately 3000 to 7000 feet. Maximum measured grade of ascent was 16 per cent. Many automobiles ascending this grade boil in the summer, but at no time in any of the tests did the machine under test boil or even get very warm. There were six or seven windfall trees across the road. The machine climbed over each of these with no more than five-minute delay in any case to chop a path through the big limbs. The ascent was made in 2 hours and 40 minutes. Near the mountain top the trailer was disconnected. The total depth of snow here was 67 inches of which 32 inches was soft wet snow. The last two miles were through very bad snow indeed. Four feet of new fallen, wet, corky snow covered about four feet of old snow and in places the snow was badly drifted. On the return trip the machine struck a snow-buried log at a speed of about ten mi/hr. It was snowing hard and the driver could not see very well. The impact was so severe that one of the passengers in the rear seat was thrown out of the machine. Two links were broken from the right driving track. From the observer's point of view, this was a fortunate accident as it afforded opportunity for the inventor to demonstrate that time required in repairing a broken track is about the same as repairing a flat tire on a car; the operation required about 30 minutes. Performance for this test was as follows: Distance traveled, 22.6 mi; maximum grade ascent, 16 per cent; total ascent, 4000 feet; gasoline consumption, 8 gallons; oil consumption, none; total elapsed time round trip, 5 hr 0 min; running time (estimated), 4 hr; average speed, 5.6 mi/hr; gasoline consumption per mile, 0.35 gallon; pay-load, 1100 pounds; gasoline consumption per ton-mile, 0.64 gallon.

This particular machine has demonstrated that it meets requirements (1) to (12) earlier mentioned in this discussion.

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DISCUSSION

R. W. CHILDRETH (U. S. Geological Survey, Portland, Oregon)--On March 27, 1945, the machine described in WORK'S paper was given a trial run observed by representatives of the United States Forest Service, Bonneville Power Administration, Iron Fireman Manufacturing Company, and the United States Geological Survey. The test run was a trip made from Government Camp to Timberline Lodge on Mt. Hood and on to a point about half way between Timberline Lodge and Lone Fir Lookout. The snow condition was poor--snow was soft, wet and sticky, of the sort that is very difficult for travel by ski.

This test was of extreme interest to me, due to the many strenuous ski trips I have made in the past several years--trips miles in length over soft, sticky snow, taking many man-hours. After having witnessed this machine in operation, I am convinced that it would have made the majority of these exhausting trips with ease, saving days of time and hard labor.

The machine is one of many such vehicles in various makes and sizes. Weight and size are two of the chief factors to be considered in a vehicle for snow surveyors. In other words, transportability is what we need. This machine, by reason of its light weight, can be transported by truck or pulled behind a passenger car on a two-wheeled trailer with ease. Also, this machine embodies factors of dependability, simplicity in design and operation, and adequate speed. The test of this machine, which was made near Timberline Lodge, Mt. Hood, proved to me without a doubt that it is adaptable for our type of work.

This machine traversed side slopes of 45 per cent, ascending a grade of 22 per cent at the same time and carried a load of 800 pounds, traveling about five mi/hr. On the road, where there was less upgrade, approximately 15 per cent, speeds up to 12 mi/hr were attained. The vehicle was driven through deep holes in the snow caused by drifting and melting. These holes were three to six feet deep on steep side slopes. Owing to the flexibility of this machine no trouble was encountered. A test for maneuverability was run through fairly open timber and brush. The only trouble encountered on this run happened when the driver attempted to turn the machine from a side slope of 15 per cent to a climb of 15 per cent in a fairly close spot. The skis sank into the soft snow, catching upon the brush. However, in a very short time (approximately ten minutes), by rocking the machine backward and forward, the snow became well packed underneath the tracks; then the machine was able to move up out of the hole. This is where a larger machine, with more traction, would be more satisfactory. We must keep in mind that the majority of trips made to snow courses and gaging stations can be reached over snowbound roads.

En route from Government Camp to Timberline Lodge we left the road to give the machine an additional test in climbing. A fairly steep slope was chosen, and upon reaching the top we discovered a very steep downgrade. This grade happened to be the uphill side of a 70° road cut about 30 feet deep. The inventor seemed to think nothing of driving his machine over this embankment. In the few seconds it took the driver to get his machine under way, two of the four passengers were very busy evacuating themselves from the machine. One of the self-evacuated passengers commented to the inventor, "All we asked for was a demonstration--we did not ask you to break up your machine," but the test was accomplished without mishap.

Transactions, American Geophysical Union Volume 27, Number III June 1946

APPLICATION OF THE COEFFICIENT OF CORRELATION TO FABRIC DIAGRAMS

Felix Chayes

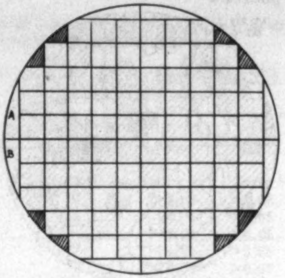
Abstract--Application of the coefficient of correlation to fabric diagrams showing weak or questionable preferred orientation is suggested and described. The coefficient of correlation is much more sensitive to weak orientations than the WINCHELL general test, and conclusions drawn from it conform more closely to published geological interpretations of diagrams on which both tests were performed. It is suggested that in general weak orientations will often yield significant correlation coefficients without departing significantly from Poisson distribution and that it may be possible to classify fabric intensities on this basis.

One of the central problems of petrofabrics is the interpretation of the contoured fabric diagram. Hypothetically, at least, one should be sure that a pattern has been satisfactorily established before one worries much about its meaning. In practice, the departure from randomness is commonly so great as to obviate the need for formal statistics in justifying the assumption of its reality. Yet there are many cases in which the casual reader who comes to the subject with little background may reasonably question, not so much whether an orientation exists, as whether or not a particular diagram or series of diagrams may constitute satisfactory evidence for it, independently of other hypothesis or information. This is clearly a statistical problem, and two possible solutions, only one of which is actually independent of other knowledge of the sample, were suggested by H. WINCHELL [1937] several years ago. It is the purpose of this paper to describe and apply a third test, suggested in 1907 by STUDENT [PEARSON and WISHART, 1943] for just such cases as this, and to my knowledge not yet applied to this particular problem.

If one places an equal-area grid over a petrofabric point diagram and records on it the number of points which occur in each square, as suggested by WINCHELL, the result will be an array very like that produced by certain types of haemocytometer counts in which STUDENT required information as to the presence and extent of local concentrations. His solution was, "In order to test whether there was any local lack of homogeneity the correlation was determined between the number of cells on a square and the number on each of the four squares nearest it; if from any cause there had been a tendency to lie closer together in some parts than in others this correlation would have been significantly positive." The correlations were found to be trifling. The problem of determining whether or not a petrofabric point diagram might have been drawn from a randomly oriented parent population is identical; a significant positive coefficient of correlation indicates an inhomogeneous population, and in this context an inhomogeneous population can only be one characterized by preferred orientation of some sort. The correlation coefficient of course provides no clue as to the validity of a pattern established by contouring; it merely tells whether the diagram is worth contouring, for if the tendency toward local concentration is not greater than might be expected in a sample drawn from a random population the only valid interpretation which may be drawn from or applied to the contoured diagram is just that no orientation has been demonstrated.

Procedure--If a standard ten-cm SCHMIDT net has been used in plotting the data, a circle ten cm in radius is divided into squares 1.77 cm on a side, each having an area one per cent that of the circle. The irregular areas at the periphery are divided as shown in Figure 1. Over this grid, the point diagram is placed. In the type of diagram to which the test may be usefully applied it is not likely that one will be bothered much by local concentration or dilution of points, and the position of the point diagram with reference to the grid is immaterial. The population of each square is tabulated in the appropriate place on a diagram like Figure 2; points falling in the shaded areas of Figure 1 are discarded. (Alternatively, INGERSON suggests that opposite triangles may be summed and entered symmetrically as single squares, thus utilizing all the data.) The result is an array of 96 squares (or 100 if INGERSON'S suggestion is adopted) containing various numbers of points.

Each square inside the dotted line of Figure 2 is then used in turn as a center, and on a frequency diagram the population of each center is tabulated against that of each of its four nearest neighbors. There will be 68 centers from a diagram such as Figure 1; each being compared with four neighbors, the final result will be a total of 272 paired values from which the correlation co-



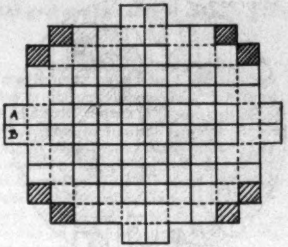


Fig. 1--96-square grid for counting out point diagram

Fig. 2--Comparison grid for recording frequencies of points in Fig. 1

efficient is computed. Instructions for this computation may be found in any standard text. A sample calculation is included below as an appendix.

Those familiar with work of this type will realize that although the procedure calls for comparisons of each center with four neighbors, the final table is a series of two-way comparisons. The number of these made from each center is thus not a matter of great consequence as long as equivalent squares receive equivalent treatment, and it may be suggested that every point on the diagram could have been used as a center for as many comparisons as possible. Each quadrant of Figure 2 would then contribute 16 additional pairs and the total of paired observations would be 336 instead of 272.

Testing the significance of the correlation coefficient--If x and y are the deviations of two variables X and Y from their respective means, the coefficient of correlation of X and Y may be written

$$r = \Sigma xy\, f(xy) / \sqrt{\Sigma x^2 \Sigma y^2}$$

and will always lie in the range $-1 < r < 1$. If there is any tendency for neighbors to border on centers similar in population to themselves, a certain portion of this tendency will be capable of representation as a linear function of the center values; r is a measure of this portion. If r is small the tendency toward segregation of like values, though perhaps real, may not be so extreme as to preclude reasonable possibility that a sample possessing it might be drawn from a population lacking it. It is customary to determine r values whose probabilities of being drawn from random populations are, respectively, 0.05 and 0.01, and to use the first as indicative and the second as decisive. If a fabric diagram yields an r whose probability is greater than 0.05 (one that might occur more than once in twenty drawings from a random population) there is no reason to suspect lack of homogeneity; if r has a probability of 0.01 or less, the existence of a significant departure from randomness in the population is beyond reasonable doubt. A table of correlation coefficients for the five per cent and one per cent levels of significance is given by SNEDECOR [1940, p. 133] and interpolation in this table gives r values of 0.12 and 0.16, respectively, for the 0.05 and 0.01 significance levels for 272 paired values. Unless there is significant departure from randomness in the rock r should not exceed 0.12 more than once in twenty or 0.16 more than once in a hundred comparable fabric diagrams. The probability of r, (P_r), shown in Table 1, below, is based on these values.

So far nothing has been said of negative correlation coefficients. If there were actually a tendency for centers to be surrounded by neighbors of significantly different population, the relation would scarcely be meaningful in terms of any of the standard structure elements, for all of these require concentration or impoverishment of points over sizeable, contiguous portions of the diagram. It is therefore the values of r between zero and one with which we are primarily concerned; negative values are perhaps as good an indication as any of insufficient data. It is worth noting that the apparent insufficiency of data as judged by the sign of r is influenced by the number of divisions in the grid. If the number of squares is greater than the number of points, for instance, each pairing of an empty square with a populated one will make a negative contribution to the covariance. The general test applied by WINCHELL is also influenced by the fineness of the grid, and if structural petrologists plan any extensive use of either test, they will do well to reach early

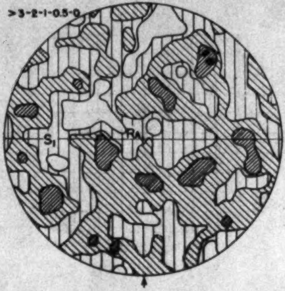


Fig. 3--400 c-axes of quartz grains from Minnelusa sandstone. RA = axes of ripple mark (after Ingerson 1940)

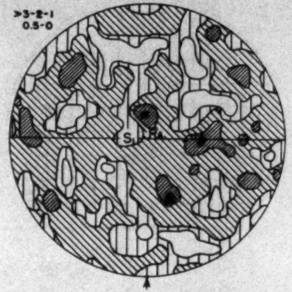


Fig. 4--300 c-axes of quartz grains from Moenkopi sandstone (after Ingerson 1940)

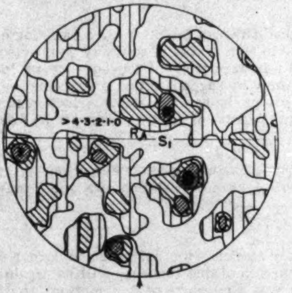


Fig. 5--200 c-axes of quartz grains from surface of ripple mark in Minnelusa sandstone (after Ingerson 1940)

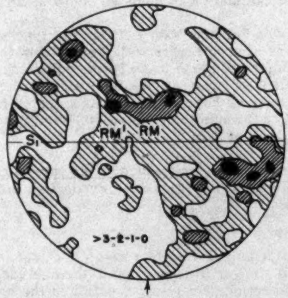


Fig. 6--300 c-axes of quartz from Baraboo quartzite. RM = axes of ripple mark on top of specimen; RM' = axis of ripple mark on bottom of specimen (after Ingerson 1940)

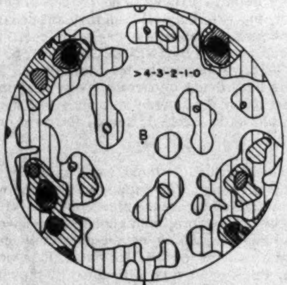


Fig. 7--200 c-axes of quartz grains from drag-folded zone in Baraboo quartzite (after Ingerson 1940)

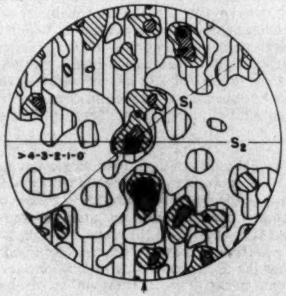


Fig. 8--200 quartz axes from Weisner quartzite (after Ingerson 1940) agreement concerning both the number of divisions on the grid and the method of pairing used in computing the correlation coefficient.

Table 1--P_r and P_W for INGERSON'S published diagrams

Figure	Figure in INGERSON'S paper	P_r	P_W
3	4	> 0.05	> 0.05
4	1	> 0.05	> 0.05
5	3	> 0.05	> 0.05
6	5	< 0.01	> 0.05
7	7	< 0.01	> 0.05
8	14	< 0.01	$0.05 > P > 0.01$

Some practical applications--Correlation coefficients have been computed for 23 partial or collective point diagrams lent to me by INGERSON. Seven of these were of well-defined poles or girdles and in each of these r was highly significant, being never less than 0.21 or more than 0.59; (the relative size of r is not of present concern since the intensity of the fabric is not under discussion; all that matters here is that no diagram which would ordinarily be considered strongly oriented was rejected by the test). The general test of WINCHELL also indicated significant departure from randomness in each of these diagrams. Of the remaining 16 point diagrams, ten form part or all of the data on which are based six published diagrams interpreted by INGERSON [1940] without reference to any statistical test. The remainder of this section is a comparison of his interpretations with conclusions based on the correlation coefficient and the general test applied by WINCHELL. The statistical part of the comparison is shown in Table 1; the first column of the table is the number of the figure in this paper, the second its number in INGERSON'S paper, the third (P_r) is the probability that the coefficient of correlation obtained from the collective point diagram used for the contouring might have been drawn from a randomly oriented population, and the fourth (P_W) is a similar probability for the general test of WINCHELL on the same grid.

INGERSON [1940] concludes that his Figure 4 (reproduced here as Fig. 3) " . . . shows random orientation . . . " (p. 560) and that his Figure 1 (Fig. 4 here) is also " . . . essentially random . . . . " (p. 559); in these cases the tests are in agreement with each other and confirm his judgment. His Figure 3 (Fig. 5 here) he says shows " . . . just enough preferred orientation to suggest that there is a tendency for the c-axes to lie in the bedding with the highest concentrations sub-parallel to the ripple mark axis . . . " (p. 560). The statistical tests are again in agreement with each other but offer his interpretation no support and he himself points out that the axis in question actually lies in an area of minimum concentration.

Figure 6 of this paper (INGERSON Fig. 5), he finds rather unconvincing, but remarks that " . . . the consistency of the partial diagrams from different parts of the thin section makes it probable that the girdle is significant" (p. 562). Consistency here can only mean general similarity between equivalent areas of the partials, a matter concerning which no information is yielded by either of the statistical tests. But the P_r value in Table 1 suggests that this reliance on the partials is unnecessary, while from the general test applied by WINCHELL it would seem to be misleading.

There was apparently no doubt about Figure 7 (also Fig. 7 here), which INGERSON says represents " . . . an incomplete girdle normal to the fold axis . . . the type to be expected in such a rock . . . " (pp. 562-3). His judgment is confirmed by the correlation coefficient, but if the general test applied by WINCHELL is to be accepted the analogy with other rocks can only mean that their orientation is also questionable.

Finally, INGERSON considers Figure 14 (Fig. 8 here) representative of " . . . a well defined girdle normal to the shear zone . . . " (p. 566). The general test of WINCHELL is non-committal, but once more the correlation coefficient indicates a definite orientation in the sample.

Conclusions--The data shown in Table 1 indicate that significant positive correlation may develop independently of and prior to significant departure from Poisson distribution. On the basis of the general test applied by WINCHELL every one of the fabric diagrams reproduced here fails to establish significant orientation in the parent population. But in three of the six diagrams the correlation coefficient indicates a significant departure from randomness, and it is just these three which were interpreted by INGERSON as clearly oriented. A fourth diagram, rejected by both tests, INGERSON considers indicative of a possible orientation. There is thus a conflict between the general test applied by WINCHELL and the geologic interpretation in four out of six cases, while the correlation coefficient conforms with the geological interpretation in all but one instance. In contouring a diagram the association of similar values is obviously more important than the departure from Poisson distribution; evidently it is also more germane to the interpretation of lower order orientations such as those described here.

It may be suggested that significant positive correlation is a sine qua non of all preferred orientation, and that the departure from POISSON distribution shown by highly oriented fabrics is a matter of common cause rather than of cause and effect. The conditions imposed by the geologist's definition of lack of orientation are just about those required for a POISSON distribution; the conditions imposed by his notion of a strongly oriented fabric are of the type which will produce large deviations from a POISSON distribution [PEARSON and WISHART, pp. 65 and 69, 1943]. Would it not be possible to define an intermediate or weakly oriented group characterized by significant positive correlation coefficient but insignificant departure from POISSON distribution? In this group might fall many sedimentary structures and perhaps also fabrics produced by mild metamorphism or the reaction of nearly crystallized magmas to lower order or intermittent stresses.

A cursory examination of the literature will satisfy almost anyone that a test of the significance of departures from randomness will only rarely be required for the evaluation of published diagrams. It is well to remember, however, that this situation reflects not only the properties of rocks but also the taste exercised by petrographers in their choice of material. As things stand, the detailed examination of what are here termed lower order fabrics offers a rather bleak prospect; results will at best be indecisive and may well be useless. An adequate reservoir of statistical tests might greatly facilitate study not only of fabrics which never become intense--such as those described here--but also of the early stages of all fabric development, whether in igneous, metamorphic, or sedimentary environment.

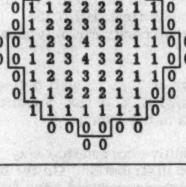
Acknowledgment--I am indebted to Dr. INGERSON not only for the data which form such a large part of the discussion, but also for encouragement, advice, and criticism without which this paper would not have been completed.

APPENDIX I--Sample plotting and calculation of r

Table 2 shows a grid distribution designed to exhibit maximum positive correlation with minimum departure from POISSON distribution; Table 3 is a frequency diagram of this distribution obtained in the fashion described in the text. The computation of r is shown in Table 4. Entries to the left and above the dividing lines of Table 4 are copied from Table 3. The f(y) column is obtained by summing the entries in each row horizontally and then summing the column vertically. Each entry represents the number of times a square of given content has been used as a center for comparison. The first entry, for instance, is 36, indicating that zero has been used as a center 36 times; since each center is compared with four neighbors, there should be nine zeroes within the solid line of Table 2. All the entries in column f(y) should be integral multiples of 4, as is the total of all comparisons, 272, which is the sum of the column. This permits rapid location of errors in the frequency table.

The y′ column, in Table 4, gives deviations for each center value from some assumed mean. The assumed mean is best located at the center of the modal class, which in this case is 1. The y′f(y) column is the product of the two previous columns, and its sum, 116, is the algebraic sum of all deviations of center values about their assumed mean. The $y'^2f(y)$ column is obtained by multiplying each f(y) entry by the square of the appropriate y′ value, and its sum is the sum of the squares of the deviations of center values about their assumed mean.

Table 2--Sample grid and general test applied by WINCHELL



					0	0					
			0	0	0	0	0	0			
		1	1	1	1	1	1	1	1		
	0	1	1	2	2	2	2	1	1	0	
	0	1	2	2	3	3	2	1	1	0	
0	0	1	2	3	4	3	2	1	1	0	0
0	0	1	2	3	4	3	2	1	1	0	0
	0	1	2	2	3	2	2	1	1	0	
	0	1	1	2	2	2	1	1	0	0	
		1	1	1	1	1	1	1	0		
			0	0	0	0	0	0			
					0	0					

x	f(x)	Theoretical POISSON dist.
0	34	33.76
1	35	35.28
2	18	18.43
3	7	6.42
4	2	2.11

$P_W > 0.9$

The lines in the lower portion of the left part of the Table are obtained in the same fashion, and provide similar information for the neighbors.

Finally, the column farthest to the right is obtained by multiplying each pair frequency by the appropriate x′, summing horizontally across the Table and multiplying the sum by the appropriate y′. For the row Y = 0, for instance, the calculation is

$$\left\{(-1)(26) + (0)(10)\right\} (-1) = 26$$

Table 3--Frequency diagram

Population of centers	Population of neighbors				
	0	1	2	3	4
0	26	10			
1	26	80	22		
2		22	36	14	
3			14	8	6
4				6	2

and so on through the Table. The sum of this column is the sum of the product of each pair of deviations times the frequency with which the pair occurs. The covariance, which is the numerator of the correlation coefficient (see computations in Table 4), is just this number divided by n, the total number of paired observations, which here is 272, the sum of the column f(y) or the row f(x).

If the deviations had been figured from the true mean of each variable, the equation given in the text would hold as stated. The true means are, in general, decimals, and hence the deviations from them are also not integral, so that the time and tedium of the computation is much increased by their use. Where assumed means are used, as here, corrections for the differences between the true and assumed values must be introduced into all further computations, but both the time required and the possibility of error in calculation are held to a minimum. The necessary corrections as well as their subsequent use in the calculation of r are shown in the lower part of Table 4. The calculation of r is much more simply performed from ungrouped values if a computing machine is available (see, for instance, Statistical methods, p. 48, P. R. RIDER, John Wiley, 1939).

Table 4--Sample computation of coefficient of correlation

Centers (y)	Neighbors (x)									
	0	1	2	3	4	f(y)	y′	y′f(y)	$y'^2f(y)$	x′y′f(x,y)
0	26	10				36	-1	-36	36	26
1	26	80	22			128	0	0	0	0
2		22	36	14		72	1	72	72	64
3			14	8	6	28	2	56	112	96
4				6	2	8	3	24	72	54
f(x)	52	112	72	28	8	272		116	292	240
x′	-1	0	1	2	3					
x′f(x)	-52	0	72	56	24	100				
$x'^2f(x)$	52	0	72	112	72	308				

Computations

1. Factors for correction from assumed to true means

$b_x = \Sigma x'f(x)/n = 100/272 = 0.377$ $b_y = \Sigma y'f(y)/n = 116/272 = 0.427$

2. Covariance $\Sigma x'y'f(x,y)/n - b_x b_y = 240/272 - (0.377)(0.427) = 0.723$

3. Standard deviations

$\sigma_x = \sqrt{\Sigma x'^2 f(x)/n - b_x^2} = \sqrt{1.133 - 0.142} = 0.999$ $\sigma_y = \sqrt{\Sigma y'^2 f(y)/n - b_y^2} = 0.947$

4. Coefficient of correlation, (r) $r = \text{Covariance}/\sigma_x\sigma_y = 0.723/(0.999)(0.947) = 0.764$

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THE ACTIVITY OF PARÍCUTIN DURING ITS THIRD YEAR

Konrad Krauskopf and Howel Williams

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On its second anniversary, February 20, 1945, the cone of Parícutin was approximately 1500 feet high, and lava flows, erupted mainly from vents at its southwest base, covered approximately 4-1/2 square miles.

During February and March, 1945, eruption of lava diminished while the explosive activity of the summit-crater increased in intensity. The Ahuan vent, at the southwest base of the main cone, continued to discharge lava throughout this period. A long stream moved slowly around the south and east base of the cone and continued northward beyond the parasitic cone of Zapicho for almost two miles, spreading across much of the great San Juan flow of 1944 and the older flow from Zapicho. In many places, the new lava was injected sill-like under these older flows, raising and arching them locally as much as 60 feet. Another long flow issued from a vent that opened on February 4 about one quarter mile west-northwest of the Ahuan vent. By the second week of March, this flow had spread northward past Canijuata as a narrow stream two miles long and had buried most of the village of Parícutin not previously inundated by lava (see Fig. 1).

During the closing days of March, two new lava vents opened close to the southwest base of the cone, between those just mentioned. These continued to emit lava throughout April and the first half of May. Indeed, by early May, the flow from the eastern one, close to the Ahuan vent, had moved eastward for two miles, extending beyond the margins of the San Juan flow in the neighborhood of Mechicano.

Early in April six other vents opened on the Mesa de los Hornitos, adjacent to the foot of the main cone, but their activity lasted only a few days and they merely discharged short tongues of lava. At and about the same time, the old ash-covered lavas of the Mesa were repeatedly fissured and differentially upheaved, presumably by buried injections of lava.

The pronounced increase in discharge of lava during April coincided with a general diminution in explosive activity. In brief, the conditions were almost the reverse of those during March. There were times in April when little or no vapor rose from the summit-crater for hours at a stretch, and one such quiet spell lasted almost a full day.

Strong explosive activity was renewed during the first two weeks of May. Indeed, on May 5, as if to celebrate the national holiday, the activity reached a violence that it had not attained previously in 1945. Bombs up to two feet in diameter were hurled almost 3000 feet above the crater rim, and the outer flanks of the cone were drenched with incandescent ejecta. Several small outbreaks of lava were also observed during the first half of May on the Mesa de los Hornitos, and one tongue pushed northward beyond the Casita on the slopes of Canijuata.

There was little change in the form of the summit-crater of Parícutin between February and the middle of May, 1945. During most of that period the crater was marked by a broad crescentic bench on the northeast side, a short distance below the rim. On the opposite side, there was a deep, funnel-shaped pit close to the bottom of which were two small bocas. These lay almost in line with Zapicho and the vent-cluster at the southwest base of the cone. Usually only the southwestern of the two bocas was active, but occasionally both were active in unison. Although the diameters of the bocas varied somewhat from time to time, they were seldom more than a few yards across. And yet it was from these surprisingly small pipes that all of the great ash- and bomb-showers were erupted. Noteworthy also was the fact that the mouths of the pipes stood only a little higher than the lava vents at the southwest base of the cone, where explosive activity was very rare and slight.

No correlation was detected between the emission of lava by the outer vents and the explosive intensity of the summit-crater. No matter whether the latter lay quiet or behaved with violence, the lava flowed uniformly from the outside vents.

The thickness of the ash-mantle over the region surrounding Parícutin, up to the middle of May, is indicated in Figure 2.

From May until the end of October, 1945, the Volcano was not under continuous observation. Reports of occasional visitors indicate that activity of the crater was much the same as during March and April--in general fairly quiet, with brief periods of stronger activity when the eruption cloud was thick and bomb-showers were frequent. The total amount of ash erupted during this

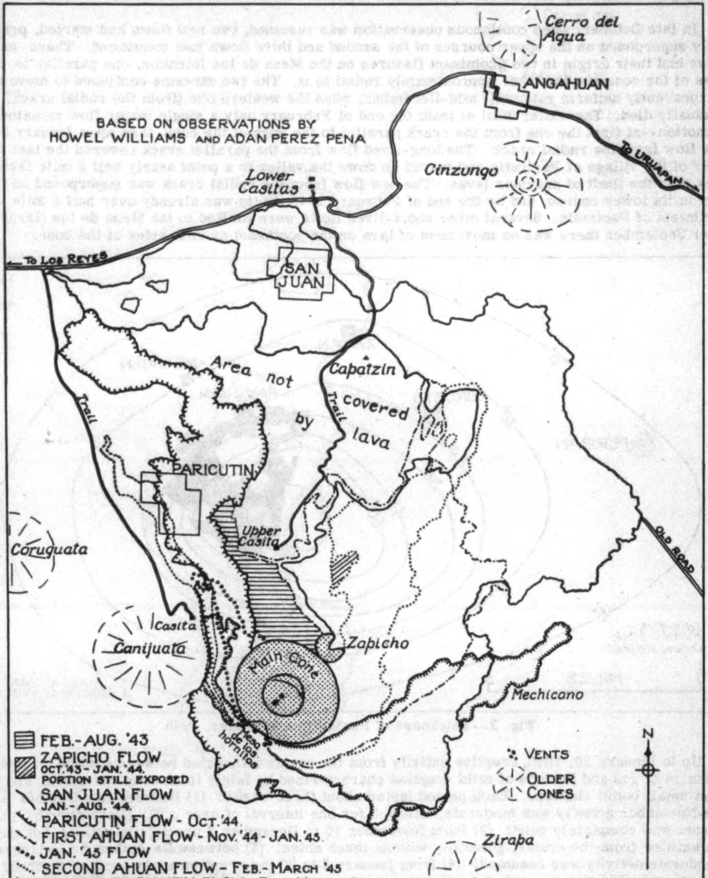
Cerro del Aqua
ANGAHUAN
BASED ON OBSERVATIONS BY
HOWEL WILLIAMS AND ADAN PEREZ PENA
TO URUAPAN
Cinzungo
Lower Casitas
TO LOS REYES
SAN JUAN
Area not covered by lava
Capatzin
Trail
Trail
PARICUTIN
Upper Casita
OLD ROAD
Coruguata
Casita
Canijuata
Zapicho
Main Cone
Mesa de los hornitos
Mechicano
FEB.-AUG. '43
ZAPICHO FLOW OCT.'43 - JAN.'44. PORTION STILL EXPOSED
SAN JUAN FLOW JAN.-AUG. '44.
PARICUTIN FLOW - OCT.'44.
FIRST AHUAN FLOW - NOV.'44 - JAN.'45.
JAN. '45 FLOW
SECOND AHUAN FLOW - FEB.-MARCH '45
SECOND PARICUTIN FLOW - FEB.-MARCH '45
FLOWS OF APRIL-MAY '45
MANY SMALL FLOWS ERUPTED FROM THE SOUTHWEST VENTS DURING 1943 AND 1945 ARE OMITTED
N
VENTS
OLDER CONES
Zirapa
0
1 Mile
0
1 Km
H.W. del.

Fig. 1--Sketch map of Parícutin lavas to May, 1945 (Williams and Perez Peña)

period must have been small, since the lavas of May and later had scarcely a trace of ash-cover until early 1946. Lava continued to flow from vents on the Mesa de los Hornitos. The three principal flows (see Fig. 3) were: (1) A flow along the southeast and east base of the cone, which split on the small cone of Zapicho and reunited north of it; (2) a flow, or perhaps more than one flow, which moved along the northwest base of the cone and then turned north along the east edge of the lava field, reaching land not previously covered just south of San Juan; (3) a flow on the west side of the lava field, whose tip barely reached new ground in the village of Parícutin. These flows had all ceased to move by the end of September.

In late October, when continuous observation was resumed, two new flows had started, practically superposed on the upper courses of the second and third flows just mentioned. These new flows had their origin in two prominent fissures on the Mesa de los Hornitos, one parallel to the base of the cone and the other approximately radial to it. The two streams continued to move at an apparently uniform rate until mid-December, when the western one (from the radial crack) gradually died. Thereafter until at least the end of February only a single major flow remained in motion--at first the one from the crack parallel to the edge of the cone, then after January 22 a new flow from the radial crack. The long-lived flow from the parallel crack covered the last vestiges of the village of Parícutin and moved on down the valley to a point nearly half a mile farther west than the limit of previous lavas. The new flow from the radial crack was superposed on this flow in its lower course, and by the end of February 1946 its tip was already over half a mile northwest of Parícutin. Several other short-lived flows were limited to the Mesa de los Hornitos. After September there was no movement of lava on the southeast or east sides of the cone.

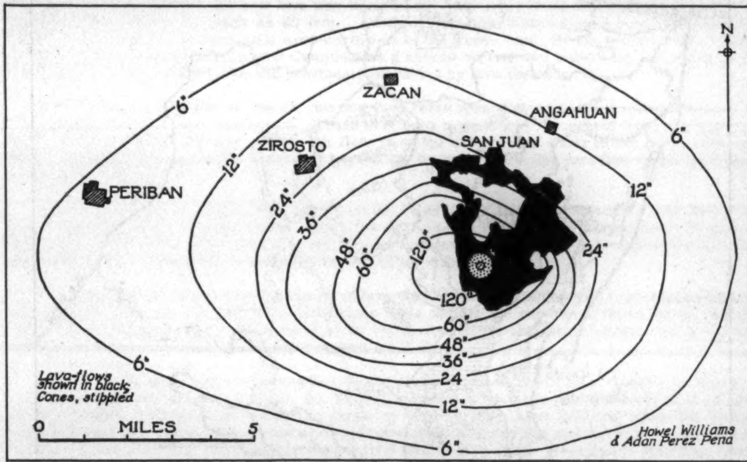

Fig. 2--Thickness of Parícutin ash to May, 1945

Up to January 20, 1946, eruptive activity from the crater alternated between periods of feeble emission of gas and periods of mild eruption characterized by fairly thick eruption clouds and frequent small bomb showers. Each period lasted about three weeks: (1) Between late October and mid-November activity was moderate, although for one interval of over a day (November 6-7) the Volcano was completely quiet; (2) from November 16 to December 7 practically nothing but gas was emitted from the crater, generally without much noise; (3) between December 8 and January 2 moderate activity was resumed; (4) from January 2 to 20 the eruption again consisted chiefly of gas emission, but was somewhat noisier than in the earlier "quiet" period. January 20, 1946, marked the apparent beginning of another active period; but this time the pattern was varied, for on January 28 the eruption cloud rather suddenly became wide and dense, showering the landscape with abundant sand and dust. All through February the Volcano continued unusually active, with a thick dark cloud, almost continuous showers of bombs, and periods of loud explosions. At times, according to natives, the eruption reached an intensity comparable with the much greater activity of the Volcano in its early days.

The form of the crater changed markedly with the kind of eruption. During the first "active" period in early November only a single vent was present, which built around itself a small cone of fragmental material. In the ensuing "quiet" period the cone was destroyed and a steep-walled inner crater with two vents was formed, the vents lying roughly on a line between Zapicho and the Mesa de los Hornitos. A striking pattern of roughly concentric steam cracks and small faults surrounded the inner crater, suggesting slumping toward the interior of the crater. During the next "active" period the pattern of cracks was destroyed and the northeast part of the inner crater was

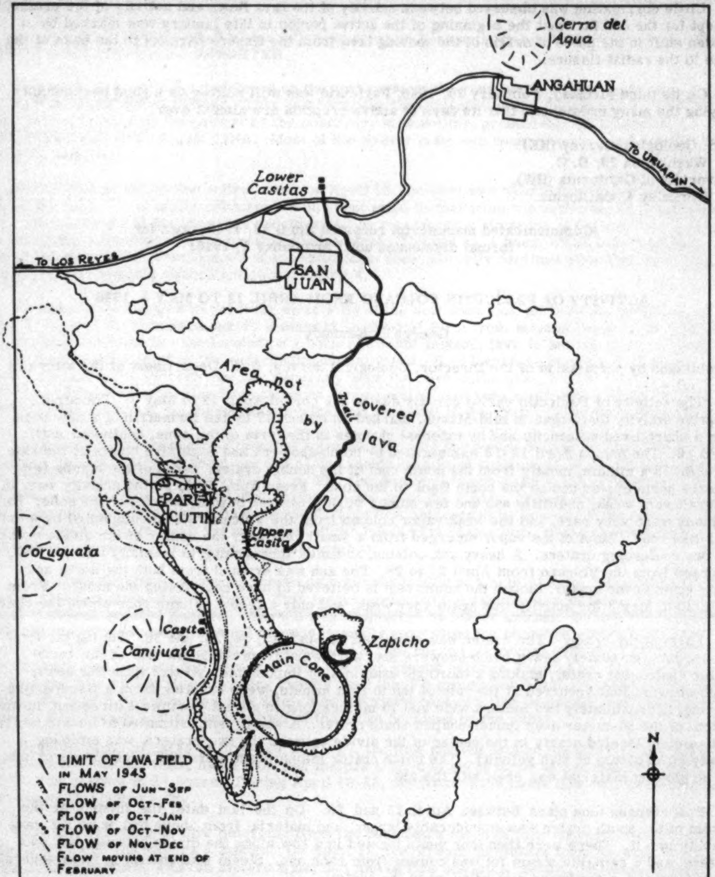
Cerro del Agua
ANGAHUAN
To Uruapan
Lower Casitas
To Los Reyes
SAN JUAN
Area not covered by lava
Trail
PARICUTIN
Upper Casita
Coruguata
Casita
Canijuata
Zapicho
Main Cone
LIMIT OF LAVA FIELD IN MAY 1945
FLOWS OF JUN-SEP
FLOW OF OCT-FEB
FLOW OF OCT-JAN
FLOW OF OCT-NOV
FLOW OF NOV-DEC
FLOW MOVING AT END OF FEBRUARY
LAVA VENTS ACTIVE AT INTERVALS BETWEEN JUNE AND FEBRUARY
N
0
1 Mile
0
1 Km

Fig. 3--Sketch map of Parícutin lavas, June, 1945, to February, 1946, using base of Figure 1 (Krauskopf)

filled by the formation of a new cone around the more active of the two vents. In early January this cone in turn disappeared, the inner crater became a northeast-southwest furrow, and the pattern of concentric cracks was reformed. The exceptional activity of late January and February was marked by an enormous increase in the size of the inner crater, to a diameter over half that of the entire crater and a depth of at least 280 feet, bringing the vent down to practically the level of the lava vent on the Mesa de los Hornitos.

Little correlation was observed between activity of the lava flows and activity of the crater, except for the odd fact that the beginning of the active period in late January was marked by a sudden shift in the place of origin of the moving lava from the fissure parallel to the base of the cone to the radial fissure.

On its third birthday, February 20, 1946, Parícutin was still putting on a good performance, belying the many predictions that its days of active eruption are almost over.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM APRIL 12 TO MAY 3, 1946

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The activity of Parícutin varied greatly during the period April 12 to May 3. The strong eruptive activity that began in mid-March, marked on March 17 by the formation of a new boca with a short-lived volcancito and by external changes in the form of the cone, continued until April 18. The period April 12-18 was marked by bomb-showers and explosive blasts at the rate of ten to 15 a minute, mostly from the south vent of the double crater. Most of the bombs fell into the north crater and on the north flank of the cone. From April 19 to 26 the activity was, in general, very weak, and little ash and few bombs were projected beyond the rim of the cone. Explosions were very rare, and the weak vapor column from the Volcano was accompanied by a dull surf-like roar. Most of the vapor emerged from a small vent near the center of the divide between the two coalescing craters. A heavy ash column, at times approaching in intensity that of 1943, emerged from the Volcano from April 27 to 29. The ash was erupted from both the north and south vents of the crater, though the south vent is believed to have contributed the most. From April 30 to May 3 the activity was again very weak, and only a feeble column rose above the cone.

Form of the crater--The crater was examined on April 13, 14, 20, and 30. During the first two ascents, extremely heavy bomb-showers shot northward from the south vent of the large double coalescing crater, making a thorough examination impossible. At that time the heavy bomb-showers that occurred at the rate of ten to 15 a minute, were erupting from a fissure-like opening, approximately two meters wide and 15 meters long in a west-northwest direction, in the bottom of the 80-meter deep funnel-shaped south crater. A small vent estimated to be one meter in diameter, located nearly in the center of the divide between the two craters, was emitting a steady jet of steam at high velocity. The north crater intermittently erupted thick clouds of ash, but no glowing material was seen with the ash.

Few changes took place between April 13 and 20. On the last date, the fissure at the bottom of the south crater was considerably larger, and material from above had begun to cave actively into it. There were then four vents located in a row along the divide between the two craters, and a separate steam jet was coming from each one. Steam was emerging from several small fissures on the broad rim adjacent to the crater.

Considerably greater changes had taken place by April 30. The caving of the walls of the south crater had progressed much further, and these walls were lined with numerous vertical scarps from one to two meters high that were actively caving headward. These scarps did not represent faults, but were the upward moving fronts along which the caving was taking place. Enlargement of the crater was accompanied by the shifting toward the north of the divide between the two craters, and the steam vents, earlier on this divide, were now well within the south crater.

The fissures on the rim, which earlier had been emitting steam, were at this time emitting heavy sulfur fumes, and they were lined with large quantities of arborescent sulfur crystals. The north crater could be examined at this time, and although found to be considerably larger than the south crater, it was not as deep and was not being enlarged by caving. It was completely stopped up by material that had dropped into it from the eruptions in the south crater, the nearly flat central part being red hot in an area of about 15 meters in diameter, but no visible gases were emerging through this material. There was no apparent correlation between the activity in the several vents in the craters.

Activity of the bocas--Most of the following notes on boca activity are taken from observations made by RAFAEL MOLINA BERBEYER.

On March 3, a new boca developed on the south side of the cone, not far from its base and near the position of the old no. 4 boca. This new boca was accompanied by the formation of a spatter cone, named Volcancito Quiquichio by the observers at that time, presumably CELEDÓNIO GUTIÉRREZ and RAFAEL MOLINA. Most of the spatter cone was soon destroyed and carried out in the moving lava.

At the time of the writer's first visit, on April 13, the lava was quietly flowing out from the side of the cone in a quantity estimated to be about equal to that from the active bocas in the past year. Development of the boca was accompanied by considerable slumping of the cone in its vicinity, and some segments slid out several hundred feet. The old no. 1 boca, which was supplying lava at the time of the development of the Quiquichio boca, abruptly declined when this new boca formed, and its activity ceased entirely on April 4.

No significant changes in the form or activity of the new boca took place in the period from April 12 to May 2. This boca varies somewhat in physical form from most of those of the past in that the lava and boca are not located on a boca ridge, but instead, lava is moving along a trough somewhat below the level of the surrounding colder lavas. It is therefore possible to approach the moving stream more closely than has generally been the case in the past, and temperature measurements of the lava emerging from the boca could readily have been made with a thermocouple. Unfortunately, however, no thermocouple wire was available to the writer at the time of his visit.

Lava flows--The extensive flows that were moving over the buried village of Parícutin in mid-February ceased to flow at about the end of that month, and their position as shown on the maps in KRAUSKOPF'S February report [Fig. 3, p. 409, this number] is about the same at present. Early in March a side tongue of lava pushed northeastward from no. 1 boca, around the west side of the cone and over the ash-covered flows of 1943. This flow had ceased to issue from its boca by March 18, and early in April the movement of the lower part of this lava, which covered the September flow south of the casita, had also ceased.

Lava from the Quiquichio boca flowed as a narrow tongue at a rate of about 300 meters a day for the first five days after its start. This tongue encircled the eastern side of the cone and had by March 3 almost reached Zapicho, where it was obstructed by higher ground. During the remainder of March the lava spread in several tongues laterally away from the cone toward the north and northwest. During April three main tongues of this flow spread northward over the 1944 flows, and by mid-April one of these had advanced over the high ground between Zapicho and the remnant of the Zapicho flow still exposed, moving rapidly over the low ground southeast and south of the upper casita. By May 2 this flow was only a few hundred yards east of a line projected south from the upper casita, though well below the level of the ridge occupied by the cabin.

Measurements of rates of flow--On April 17, the flow moving around the north side of Zapicho was about 300 meters wide, had a front ten meters high, a slope of three to five degrees, and a speed of 28 meters in 24 hours. During April 19-28, the front of the same flow was advancing an average of 20 meters a day.

On April 17, the lava flow emerging from the boca had a slope of four degrees, was 15 meters wide, and flowed two meters a minute. On April 18, the stream 30 meters from its boca had a slope of four degrees, was ten meters wide, and moved five meters a minute; 300 meters from the boca the lava stream sloped ten degrees; it was 20 meters wide, and flowed two meters a minute.

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RESEARCH COMMITTEE ON SNOW, WESTERN SNOW CONFERENCE, 1945

J. E. Church, Chairman

The Research Committee on Snow was organized in 1942 in response to a feeling that the accumulated snow data should be analyzed to search for possible solution of inconsistencies and errors that had appeared in the forecasts of stream flow. At the Snow Conference at Sacramento HAROLD CONKLING [1941] voiced the need, and FRED PAGET, Chairman of the Conference designated the following members to form the Committee: J. E. Church, Chairman; R. A. Work; Joseph Kittredge; George D. Clyde; Ralph L. Parshall; and Merrill Bernard. The accumulated data unfortunately still remain unanalyzed, but research and inquiry have gone steadily on.

Many questions submitted by the Committee to the Chairman are highly specialized, as are the following by JOSEPH KITTREDGE (the University of California, Berkeley, California): (1) Can stream-flow forecasting be improved by locating part of the snow-survey courses under trees? (2) Is snow density the best index of the melting of snow? If not, what other measure would be both practicable and more reliable? (3) What are the relative merits of density and snow quality as indices of melting? (4) Can runoff from snow be expressed as a function of several factors such as density and water equivalent of snow, insolation, degree-days above freezing, rainfall, and snowfall during melting season, to give a more reliable forecast than would be obtained by the use of only one or two factors? (5) Can we secure confirmation and refinement of findings of W. T. WILSON [1941] on thermodynamics of snow melt? For example, does snow melt by condensation on the snow surface increase with wind velocity?

G. D. CLYDE (Utah State Agric. Coll., Logan, Utah)--I am convinced, as a result of our research in Utah, that we can considerably reduce the number of observations on our long snow courses, and that in many places we can eliminate entire snow courses. I expect to prepare a progress report this spring on the Utah work which will summarize our findings in this regard. I feel that probably the most important items of research that still need to be done lie in the field of watershed yield, rate of melting and its effect on yield, and the effect of the condition of the soil mantle during the melting season. I think we should also concentrate our efforts on the forecasting of occurrence of runoff. This, I am sure, will be much more difficult than forecasting quantity.

RALPH L. PARSHALL (Soil Conservation Service, Fort Collins, Colorado)--There are many problems confronting us in connection with the forecast of water supplies based on snow surveys. I believe it would be of interest to learn something of what we have been able to accomplish where the fall flow of streams is made a part of the forecast for April 1. Can you not discuss at the meeting of our Colorado River Water Forecast Committee the problem of forecasting runoff based on April 1 snow surveys when a large portion of the snow cover at high elevations occurs during May?

But more fundamental than all is the feeling of MERRILL BERNARD that precipitation rather than snow cover is the most reliable basis for forecasting the runoff of both rain-fed and snow-fed streams and has presented a system of probabilities to the user of water throughout the progress of the water year. Where precipitation from November to March is practically equivalent to the snow cover on April 1, the forecasts should be similar. Where the snow cover is markedly less, the runoff for April-July should correspond more closely to the snow cover. His method and that of snow surveying will be presented further on in detail. Fortunately, sufficient progress has now been attained to report on the following projects: Snow sampling; precipitation gages; snow melt; normals; effect of soil moisture; precipitation rather than snow cover as basis for forecasting seasonal flow; special forecast problems; and transport.

Snow sampling

Cutters--Another wide step has been taken by JOHN T. RYAN, Superintendent of the University Shops, Reno, Nevada, toward solving the problem of penetrating frozen snow and ice layers. The original tooth cutter had been restored, but easier penetration was still desired. The teeth have now been reduced in number and lengthened to avoid the rapid packing and refreezing of the ice dust in the cutter (Fig. 1). **FRED PAGET** comments that the ranger snow surveyors in Sequoia National Park years ago cut out the alternate teeth of their snow cutter to accomplish the same result. Far les pressure on the sampler is now required.

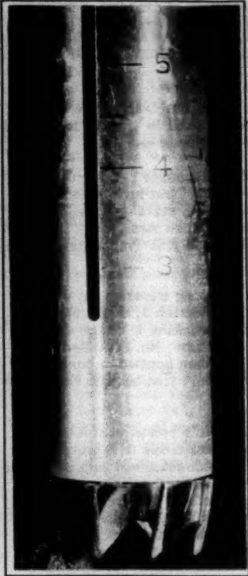

Fig. 1--Improved snow-cutter

Sticking of sampler tube--The sticking of the sampler tube in frozen snow has long been known and is associated vividly with sunny sky and aluminum metal, which warms quickly but chills suddenly. The solution for this was to keep the sampler in the shade or wait for nightfall.

This past winter the conditions have been reversed. The snow has been moist but the air cold. The phenomenon was experienced in places as remote as the High Sierra, the Ruby Range in eastern Nevada, the Olympics of Washington State, and as high as 8400-foot altitude. It accompanied the open winter. The only preventive for this condition is to wait for milder air temperature, that is, temperature above freezing, or to heat the sampler in the Sun if the wind does not nullify insolation, or warm it over a fire of wood or kerosene. Small tins of "canned heat" called Sterno might serve. The steel samplers will retain the heat longest.

The reports by surveyors are so uniform yet so varied that they deserve recording. The Chairman also shared the experience. The use of Fuchsine dye could have demonstrated the presence of moisture in the snow beyond doubt.

PHILIP S. COWGILL (Sierra Pacific Power Company, April 13, 1945)--During the season of 1945 considerable difficulty in obtaining good cores was experienced owing to freezing in the tube. In most cases this difficulty occurred during below-freezing weather. There were several layers of crust, with loose snow between. A few inches below the surface the snow seemed to be quite damp and would freeze solidly in the tube after it had been driven a few inches. It was found that by warming the tube over a fire and then driving as rapidly as possible, good cores could be obtained, but they were likely to freeze in the tube on withdrawing it from the snow. It was also found that if the tube was thoroughly dried during the warming process, results were better. The objection to this method is the time consumed in warming the tube for each sample. Also unless considerable care is used the shellac coating may be melted and the metal damaged. In one district it was found that the shellac was badly chipped off from the inside of the first joint of the sampler, and much difficulty was experienced in driving, the core freezing solidly in the first 12 or 15 inches. As no shellac was available, the inside of the sampler was swabbed with kerosene. This treatment proved to be effective, but it had to be repeated after every four or five samples.

Some of the parties have tried lubricating oil diluted with gasoline. This has proven generally effective, but on March 1, under conditions of zero or near-zero temperature, combined with rather wet snow under the surface with about a foot of newly fallen snow on the surface, it seemed practically impossible to obtain satisfactory cores. The conditions this year have been unusual, and what is even more unusual, have persisted throughout the season.

WALTER J. HERZ (Sierra Pacific Power Company)--At 8400 feet in the Central Sierra on the Lake Lucile Snow Course, only five of 37 snow samples could be obtained because of freezing of the snow sampler in the snow despite the fact that the air temperature was 14°F, and a storm was in progress. The snow sampler also was made of steel and not the sensitive aluminum.

The log of this survey was as follows: Date, March 5, 1945; location, Lake Lucile; at Station 1, snow depth, 109 inches, length of core, 95 inches, and water equivalent, 43 inches; at Station 2, snow depth, 121 inches, length of core, 115 inches, and water equivalent, 46.5 inches; at Stations 3, 4, 5, 6, 7, 10, snow froze; Stations 8 and 9 skipped; observations ended at 15^h45^m; windy; temperature 14°F. The snow must have been moist, but it was impossible to retrace the long route to check this by Fuchsine dye.

J. E. CHURCH (Soda Springs Experiment Station)--The ultimate effect of air temperature on that of the snow was demonstrated in a series of experiences of sampling warm snow in air temperature that froze the snow in the samples.

The following survey notes indicate the changing phases:

Donner Pass Course--(March 31) Warm air, cold snow. Steel sampler drives deeper than duralumin but even the steel stuck. Balmy day (60°F max). Apparently frost in snow at 150 inches. Snow cold at six inches by dye test. (Later: Yet my face was severely sunburned.)

Soda Springs Course No. 1--(April 1) Sampling difficulties. Measurements 1-4 were made easily yesterday, and the entire course could have been completed quickly, but further sampling was postponed to share in the survey of the course at Donner Pass. A new start was made today at measurement 5 at 09^{h}30^m. An east wind was blowing and air temperature was 19°F. The sampler was so cold that moist snow stuck to it, as at Lake Lucile, and probably at Trout Creek in the Ruby Range.

The sampling was laboriously continued until 14^{h}30^m when the following experiences were encountered, ending the day's effort: No. 10--Snow clogged in sampler section 1, froze; No. 11--Bottom of snow cold and dry, core fell out readily, ideal; No. 12--Snow sticking in cutter and one foot above, but only slightly; No. 13--Sampler clogged, snow freezing in tube; No. 13a--Snow frozen in tube, snow moist, froze even to cleaning hook (yet dye green when applied to core; air is too cold; dye also is green on surface of snow; the snow is red, however, just beneath the surface where sheltered in the Sun). So gave up.

At 18^{h}00^m, April 2, the effort was renewed with unexpectedly favorable results as follows: No. 13--Snow dry, crumbles, dye green throughout, no adhesions, but snow froze to sampler when latter lay on the surface in the Sun; No. 14--Perfect release; No. 14a--Adhesion and packing, some freezing in cutter, but this is on the grassy, moist bank of creek, snow hard elsewhere. (Query: Yesterday the snow cover was moist, today dry. Why? Due to descent of air temperature? The depth is 82 to 92 inches. It is the old mystery of snow drying or freezing quickly with the coming of night. H. LANDSBERG suggests that air circulation through the porous snow may cause it. V. A. CONRAD calls similar downward directed percolation of air "cold convection.")

The use of heat, recommended for adhesion when the snow is moist and the air is cold, finds another application in ski waxes tried as an improvement over the original shellac and emergency kerosene. The success is obvious but the tests were made mostly when the air was warm and the snow was cold. The story is told in detail by its originator.

GEORGE A. LEWIS (Los Angeles Department of Water and Power, April 10, 1945)--We have now concluded our experiment for this year, on the new method of waxing sampler tubes, and although we were unable to find the severe sampling conditions we hoped for, I am happy to report that under circumstances normally considered bad, we had very good success. In order that you may use this information at the Portland Conference, I shall recapitulate that which I reported to you at the Los Angeles Meeting and add whatever data we have gathered since that time.

During our February survey, sampling conditions were generally bad, particularly so on the upper Mammoth Course. To survey this course requires a long ski trip. It is usually impossible to take samples during the middle of the day, because of excessive depths (up to 20 feet) and the usual wide divergence between temperatures of air and snow. On this occasion, a new man retarded the progress of the party somewhat, and they did not arrive at the top course until noon.

From experience, DAVID McCOY, who was in charge of the party, thought that it would be useless to try cutting samples at that hour, but rather than wait until sundown, he decided to try waxing the tubes with different type ski waxes to see if that would overcome clogging. The results were so surprising that they ran out the course immediately and obtained excellent cores. The mean depth of the course was 111.7 inches and the mean core length 106.3 inches. No temperatures were taken. So that you may better visualize the adverse conditions overcome, the following is quoted from the notes made on that course: "50 to 70 inches of new clogging snow on old cold snow made sampling impossible until we waxed tubes. There were three crusts in old snow. Water and snow falling from trees all day. Cloudy and warm." From the above you will recognize the old familiar condition of "hot air and cold snow." There is but one worse condition of sampling--that of "hot snow and cold air." It was to determine whether or not we could successfully overcome this latter state that we did considerable research during our surveys in April. In some cases our tests show snow in which free moisture was present; however, the temperature divergence was not excessive. The tabulated data reveal a great improvement over former results from these same courses. It may be well to add that sampling was conducted during the warm hours of the day, and every attempt was made to look for "tough" sampling conditions.

McCOY was so enthusiastic about his discovery that we adopted his method on subsequent surveys and met with very good results. Our tubes, as you know, are the original steel type, and heretofore we have used only a coating of Valspar varnish to prevent clogging. The first treatment of Gerbers Schuss ski wax was applied in the field by warming the tubes over a campfire and then drawing a rag swab (covered with Schuss) through the tubes, then polishing. Before our last survey all our tubes (except one) were given similar treatment in our shops, and it was unnecessary to re-treat any of the tubes in the field. The wax was put on over the varnish base and polished (with a swab) to a high finish. I might add here that I suspect this thorough polishing is the critical factor in obtaining a clog-free tube. The outside coating was applied in the conventional manner, and also polished. This waxing and polishing has a mechanical effect on the tube also--considerable depth may be plumbed with far less effort due to the reduction of skin friction at the joints. This latter advantage was noted by all our parties.

The following excerpts from our notes during April should prove interesting. Figures shown are means for the course.

Cottonwood Station 1--Elevation 10,600 feet, depth 52.8 inches, core 51.4 inches; temperatures at start, air 24°, top snow 26°, middle snow 27°, bottom snow 28°; at finish, air 21°, top snow 22°, middle snow 24°, bottom snow 24°. Remarks: Weather clear with temperature below freezing; excellent sampling; Stations 15 + 10 and 15 + 90 have been flooded (see previous reference to this condition on survey of February, 1942); snow wind-packed with one to three crusts below top, and as many as five crusts in vicinity of flooded stations; bottoms mostly dry; creek completely covered in this area.

Cottonwood Station 2--Elevation 11,100 feet, depth 57.6 inches, core 56.2 inches; temperatures at start, air 20°, top snow 18°, middle snow 21°, bottom snow 24°; at finish, air 23°, top snow 17°, middle snow 20°, bottom snow 23°. Remarks: Weather clear, with temperature below freezing; light breezes intermittently; snow wind-packed with one crust below top from 12 inches to mid-depth; bottoms mostly dry; lakes and creeks completely closed; sampling excellent.

Big Pine Station 1--Elevation 10,000 feet, depth 97.8 inches, core 95.2 inches; temperatures at start, air 30°, top snow 26°, middle snow 27°, bottom snow 30°; at finish, air 26°, top snow 24°, middle snow 26°, bottom snow 28°. Remarks: 30 inches dry powder-snow on old hard crust; no melting; no runoff; ground mostly thawed; snow well packed and granulated below powder; samples came out very good; lost several through bit-end of tube; considered sampling conditions poor at beginning of course, but sky became overcast and had good sampling conditions thereafter.

Big Pine Station 2--Elevation 9700 feet, depth 77.1 inches, core 73.6 inches; temperatures at start, air 26°, top snow 24°, middle snow 30°, bottom snow 31°; at finish, air 28°, top snow 29°, middle snow 29°, bottom snow 30°. Remarks: 30 inches powder-snow on old hard crust; no melting; no runoff; ground thawed; cores well packed and granular below powder; sky was overcast when sampling started, cleared when at Station 3 + 50 and Sun came out hot; air warmed up and wind died out to light breeze; samples came out well regardless of conditions; had Schuss wax on tubes; sampling conditions from Station 3 + 50 ahead were considered adverse.

Big Pine Station 3--Elevation 9800 feet, depth 76.0 inches, core 72.4 inches; temperatures at start, air 24°, top snow 21°, middle snow 26°, bottom snow 30°; at finish, air 20°, top snow 22°, middle snow 26°, bottom snow 28°. Remarks: Windblown crust, 24 inches powder-snow on old hard crust; no melting; no runoff; ground mostly frozen; hard wind blowing; snow flurries.

Minarettes Station 1--Elevation 8300 feet, depth 77.5 inches, core 70.8 inches; temperatures at start, air 22°, top snow 18°, middle snow 28°, bottom snow 29°; at finish, air 29°, top snow 22°, middle snow 32°, bottom snow 32°. Remarks: The top snow, two to six inches of powder, was turning to a clogging snow owing to the hot Sun on course; it was hard to get full cores under trees because of the five crusts which seem to have air pockets under them; bottom snow is corn; soil is damp and soft; no ice; drifts on upper end of course; the only exposed ground is on the south slopes covered with low brush; all tree slopes are heavily covered.

Minarettes Station 2--Elevation 9000 feet, depth 112.8 inches, core 109.1 inches; temperatures at start, air 24°, top snow 23°, middle snow 29°, bottom snow 31°; at finish, air 28°, top snow 27°, middle snow 28°, bottom snow 32°. Remarks: Snow was so wet that water could be squeezed from it like a sponge; two to ten inches of powder-snow in shaded areas and clogging powder in areas exposed to Sun; two very hard crusts on bottom; soil damp and soft; clear and warm; no pockets around trees; drifts in area; sampling good.

Mammoth Station 1--Elevation 9500 feet, depth 141.6 inches, core 139.5 inches; temperatures at start, air 33°, top snow 31°, middle snow 30°, bottom snow 32°; at finish, air 32°, top snow 32°, middle snow 29°, bottom snow 31°. Remarks: Clear, light west wind; warm; top snow clogging powder in shade, and slopes wet in Sun-exposed areas; soil damp and not frozen; sampling very good; no wind-bare spots on Mammoth Mountain.

Mammoth Station 2--Elevation 8300 feet, depth 78.7 inches, core 73.6 inches; temperatures at start, air 26°, top snow 22°, middle snow 30°, bottom snow 30°; at finish, air 27°, top snow 18°, middle snow 28°, bottom snow 26°. Remarks: Clear, calm, and cold; breakable crust with powder under it; hard to get good cores under trees because of crusts; sampling very good in open spots; soil damp, not frozen; trees white with frost above course.

Rock Creek Station 1--Elevation 8700 feet, depth 47.6 inches, core 42.2 inches; temperatures at start, air 28°, top snow 18°, middle snow 28°, bottom snow 30°; at finish air 35°, top snow 16°, middle snow 25°, bottom snow 32°. Remarks: Top snow crusted, will hold person's weight without skis; four under-crusts and two air pockets making it hard to get full cores; dirt very moist; bottom snow corn and wet, mushes out when dumped from tube; south-exposed slopes of canyon nearly bare of snow up to fourth ridge; only other bare spots are the high ridges.

Rock Creek Station 2--Elevation 9050 feet, depth 46.7 inches, core 40.0 inches; temperatures at start, air 36°, top snow 30°, middle snow 29°, bottom snow 31°; at finish, air 40°, top snow 32°, middle snow 30°, bottom snow 32°. Remarks: Sampling good but hard to get cores owing to four crusts and air pockets; at start of course snow was solid, by the time we were through our skis sank in three to four inches in corn-snow; no new slides in area; no bare spots around trees; soil damp, not frozen.

Rock Creek Station 3--Elevation 10,000 feet, depth 58.3 inches, core 53.2 inches; temperatures at start, air 42°, top snow 32°, middle snow 28°, bottom snow 32°; at finish, air 34°, top snow 32°, middle snow 28°, bottom snow 31°. Remarks: Top snow soft corn and soft wind-blown powder; drifted snow in trees; sampling better in drifts because of the absence of crust; three noticeable crusts, one very hard, which required quite a little twisting of tube, with air pocket under it; soil soft and damp, not frozen.

We took samples on the upper Mammoth Course in conditions which had always given us trouble before. The only times snow stuck in tube were twice in section no. 5 which was not waxed. Here the snow jammed. We could tip tube-cutter end down and snow moved freely from tube no. 4 down but stuck solid in no. 5. One man can handle the long tube much easier than before. There was no need for the wrench even on the deepest observations. On lower Rock Creek where it was hard to get full cores owing to crusts we disconnected tube no. 1 and put it down in the usual way. Looking down the tube we observed that the core was free from tube, but that every time the cutter went through a crust the core failed to come up for the next two to three inches, making it impossible to get good cores.

One section of the tubing (mentioned above) was given only the regular coating of Valspar varnish and used as a control. When this section was placed in service in conjunction with the waxed sections it clogged whenever conditions were adverse while the waxed sections continued to function perfectly.

Although we have experienced excellent results with this method, it is not offered as the panacea for all tube trouble, and we now pass it on, for the benefit of "frustrated" snow surveyors in general, with the hope that it may prove to be as effective for them as it has been for us.

Snow-course markers--The iron pipe snow-course markers have been found to withstand rubbing by stock on the ranges providing they have the larger diameter of two inches and are set in a heavy core of concrete. The paint may be rubbed off. The pipes should be tall enough to place projecting signs above the reach of the cattle. A height of ten feet is optimum. With the larger diameter the pyramid of rocks at the base often suggested becomes unnecessary.

Precipitation gages

Storage gages--During the past year the conical United States Engineers gage has been simplified by the United States Weather Bureau and the United States Engineers to the type known as the Sacramento gage. Its increasing diameter, from the eight-inch orifice to the 18-inch and larger bottom provides capacity for an annual precipitation of 40-inch water equivalent, together with sufficient calcium chloride solution to prevent freezing of the contents during the early and cold part of the season and sufficient concentration for the milder balance of the year. The expanding walls should provide sufficient room for wind eddies to lose intensity and the snow catch to settle and become absorbed without undue adhesion to the walls. This does not, however, protect the orifice from sleeting and becoming capped with frost or snow as happened to all of the precipitation gages at Soda Springs in the unusual storm of November 9-12, 1944. Five days elapsed before the Sun returned and by its insolation cleared them all. The maximum loss of precipitation during this period was 3.18-inch water equivalent. This gage has become standard for areas of heavy precipitation or long-period collection. Where the total annual precipitation is far less, a tank of similar form but smaller capacity is provided.

Recording gages--The Stevens Q-gage, which has a capacity, with calcium chloride solution, of 18-inch water equivalent, continues dependable. Its pen still traces for one to two years without refilling. Some improvements in its orifice have been made by R. W. GERDEL to increase its capacity. It is being used by the United States Engineers and the United States Weather Bureau in their joint snow-study program.

The Stevens large-capacity W-gage has required some heavier suspension cables, but its motor battery has functioned two years and its siphon pen will complete a full year without refilling. The present batteries have been heavily insulated to protect against extreme changes of temperature, but it is now planned to test cells in an ordinary cabinet without insulation. Primary cells are necessarily employed, for dry cells in prolonged cold on Mount Rose (10,800 feet) have failed and even cracked open. The Stevens W-gage is being developed into a radio-reporting gage for locations uninhabited or not easily accessible.

Towers--The three optima in precipitation-gage towers are stability against overturning, lightness, and rigidity. Rigidity, however, is a prime requisite only in case of recording gages where the pen is directly connected with the reservoir. Wind vibration would scarcely be recorded by Stevens W-gage with its electrical attachment of the catch and recording mechanism. But even if the tower is quite rigid, wind suction acting on the delicately poised reservoir will cause oscillation of the pen in proportion to the violence of the wind and the width of the scale on the record chart. The use of cables to assure stability and rigidity must meet the handicap of stock in summer and snow in winter. The classic example of the former is the shock caused the interior of the Stevens Q-gage by horses running into the guy wires attached to the tower. Not only were the pen and pen-arm shaken off, but the contents of the reservoir were splashed over the bearings, ultimately causing friction and angularity in the record. Cables make an attractive rubbing place for stock and can be protected against them only by fencing the tower or building guard rails on both sides of each cable.

The heavy load of settling snow in the winter leaves sagging or broken cables in the spring. The use of spiral springs suggested by JOHN C. STEVENS, to ease the strain and yet keep the cables taut, resulted this past winter in breaking the springs. A heavier set will be installed this coming winter. The question has been raised whether cables, especially those with springs, do not impart additional vibration to the tower, particularly in summer when the entire length of the cables is exposed to the wind. A test of cable effect is desirable. Meanwhile towers without cables are becoming customary.

Wind-shields--The value of wind-shields in improving the catch of precipitation gages has been further demonstrated by prolonged tests at Soda Springs and particularly by a comparison of gages by the United States Weather Bureau at Norden, where two sets of gages (shielded and unshielded) were located on towers in a forest glade and in the open meadow. The following data were provided by ASHTON R. CODD, who shared with R. W. GERDEL in the tests:

Norden, January 5, 1944, to April 19, 1945--In meadow; unshielded, 14.50 inch, and shielded, 19.10-inch water equivalent; in glade; unshielded, 18.10 inch, and shielded, 21.60-inch water equivalent.

The shield, as pointed out by H. LANDSBERG, is more effective than the forest in modifying wind current, the gain of the shields being 4.6 inches and 3.5 inches as compared with 3.6 inches and 2.5 inches for the forest.

Superiority of a shielded over an unshielded gage even in adverse locations is shown by a test in Donner Pass (Table 1), where upslope winds are accentuated by the rocks and storm winds are violent. To neutralize somewhat the effect of the wind, the shield was made of slats placed close together but capable of closing upward and inward at their base around the throat of the gage. When the winds are westerly, as usual, the shielded gage is fully exposed to the wind, and the unshielded gage is sheltered; the reverse is true when the winds are easterly.

Table 1--Comparison of data secured by shielded and unshielded precipitation gages at Donner Pass, May-June, 1945

Date	Precipitation		Wind		Precipitation at Soda Springs (No. 1 unshielded)
	Station gage (unshielded)	University gage (shielded)	Direction	Range in velocity	
May	in	in		mi/hr	in
6	0.02	0.02	WSW	3-31	0
10	0.33	0.34	W-WSW	3-29	0.55
12-13	0.08	0.20		13-41	
14	0.08	0.12	SW-WSW	14-29	0.48
16	0.33	0.39	SW-WSW	20-59+	0.60
17	T	T	SW-WSW	33+-50+	0.02
18	0.02	0.03	WSW	14-34	0.09
19	0.04	0.07	SW-WSW	2-34	0.36
27	0.15	0.17	WSW	2-11	0.07
28	0.01	0.01	SW-WSW	2-13	0.11
29	0.11	0.11	SW-WSW	2-13	0.11
30	0.09	0.12	WSW	3-21	0.10
31	0.02	0.02	SW	15-23	0.14
Total	1.28	1.60			2.63
June					
2	T	T	WSW	27-42	
3	0.19	0.22	SW	12-24	0.23
4	0.32	0.36	SW	7-29	0.36
5	0.25	0.27	WSW	8-24	0.63
6	0.09	0.11	SW-WSW	3-19	0.36
8	0.32	0.33	WSW	5-23	0.00
23	0.20	0.22	WSW	5-16	0.17
Total	1.37	1.51			1.75

Note: Values of precipitation are inches of water equivalent for the 24 hours preceding $17^{h}00^{m}$ of date shown.

Unfortunately, the wind-shield was not made tight until May. Consequently the available comparison covers only a period of milder weather and precipitation. The comparative data were generously obtained by the Airway Communication Station for the Nevada Agricultural Experiment Station.

The catch of the shielded gage for both months was approximately ten per cent higher than for the unshielded, despite the persistent handicap of westerly winds. The precipitation was probably mainly wet snow or rain.

A desirable project is the determination of the relative efficiency of shielded gages at low and high wind velocity. Data for wind are available at Soda Springs and at Donner Pass, and detailed comparison will be made this coming winter. Unfortunately no measurements of wind were made at the gages at Norden midway between the two extremes.

Snow melt

The problem of snow melt is now being attacked from various angles, but the data have not been fully tabulated. Trends, however, are clear.

Length of melting day--At the altitude of 7000 feet, and probably even at 6000 feet, at latitudes as low as 38° north, the length of the melting day varies from six to eight hours during the runoff period of April to May. This has also been noted in midsummer on the inland ice of Greenland at the Arctic Circle at an altitude of 1500 feet. The shortness of the daily period of melting is fortunate where snow storage rather than water storage must be depended on for the growing of crops. The quantity of flow is also fortunately cut down.

Because of the fixity of the temperature of snow at or below 32°F, the melting is slow to begin in the morning and prompt to cease in the evening, even while the Sun is still above the horizon. The snow surface usually congeals while the air temperature at the head height of the usual exposed thermometer is near 40°F or higher. This has been observed also on Mount Washington, New Hampshire. Therefore the minimum air temperature of 32°F in climatic records can no longer be used as an indicator of the cessation of melting. The temperature band of normal melting is by present standards from 40°F to 65°F, based on the traditional technique of climatic measurements, which should yield to the more exact method of obtaining measurements of temperature and humidity at the surface of the snow. LANDSBERG suggests that wet-bulb rather than dry-bulb measurements be taken, since the snow, being wet during melting, is covered by a vapor blanket. Furthermore, the wet-bulb temperature represents more closely the temperature of falling rain, which may accelerate melting. The minimum of 40°F can not apply where the air is turbulent, as in a Chinook. Then the surface temperature may be identical with that higher up.

Duration of diurnal percolation--The duration of diurnal percolation is still an open question. GEORGE D. CLYDE has found melt-water percolate throughout the night in the Wasatch of Utah while R. A. WORK has noted in the Cascades at Crater Lake, Oregon, that percolation ceases promptly at the cessation of surface melting. In the Sierra Nevada percolation slows down but may persist through the night. In the case of snow on railway snow sheds, copious percolation has been observed well beyond midnight.

Is the difference in the length of the period due to the difference in the depth of the snow cover? The snow in the Wasatch is relatively shallow and in the Cascades unusually deep. In the Sierra Nevada the snow is of medium depth, or approximately eight to ten feet. Depth, texture, and temperature of snow are controlling factors in the problem.

Capillarity or percolation control--The capillarity of new snow and its effectiveness in serving as a protective covering for old snow has long been recognized in forecasting [CHURCH, 1927]. At the Soda Springs Laboratory GERDEL has obtained data which "indicated that the free water-holding capacity of a ripe snow pack was usually below ten per cent, and that under conditions where melt water or rain was not being added to the pack at a rate greater than the transmission capacity, the water-holding capacity of a deep, ripe snow pack was approximately 0.4 inch per foot of snow of 50 per cent density."

Free-water transmission rates as measured at Soda Springs varied between 0.5 and 5.0 inch per foot per hour. Variations appeared to be associated with the extent and thickness of the ice planes in the samples used.

Determining presence of free water in snow--A laboratory study of the accuracy of the calorimetric method of determining the quantity of free water present in snow has been made by S. W. LEIFSON of the Department of Physics of the University of Nevada, as reported in the Semi-Annual Report of the Cooperative Research Station at Soda Springs 1944-45. GERDEL and JOHN BRIDGES have conducted studies on electronic procedures for the determination of the free-water content of the snow pack.

The presence of free water in snow can be determined quickly by Fuchsine dye, and procedures for its application to the snow cover have been worked out [CHURCH, 1943(A)]. A test is now contemplated to determine whether the intensity of the dye color can be translated into per cent of free water as 0-25, 26-50, 51-75, 76-100. A color card of four color intensities might provide a chart for visual identification of the free-water condition of the snow, but exceptions could well be numerous. The relative amount of free water is also subject to diurnal change. The transition of the dye color to purple indicates that the snow was once wet but has refrozen.

Normals

Parallel normals--The problem of normals is more intricate than merely obtaining a long-time average. For example, the long trend in one region, as the Sierra Nevada, can not reliably be identified with that in the upper Humboldt Basin in eastern Nevada [SAGER, 1933], nor can the trend in the Columbia Basin be considered as similar to either of them. Once, while increasing water and decreasing power demands were prevailing on the Columbia, the opposite was true in Nevada.

The prime essential in forecasting stream flow is to create time-parallel normals between the precipitation or snow cover and the resulting runoff. For example, there is a great disparity between the 66-year and 20-year (1925-44) normals of runoff for April to July of the Columbia River near The Dalles, Oregon, the former being 84,800,000 and the latter 70,700,000 acre-feet, or approximately 20 per cent larger. Since the normal or mean for precipitation used by the United States Weather Bureau is based on a 20-year record and the mean for snow surveys on only ten years, the forecast of runoff will more nearly approach the actual if based on a normal of similar period.

Median versus mean--The median first urged in the Western Snow Conference by H. T. GISBORNE of the Forest Service and adopted by the United States Geological Survey for its Water Resources Review has now entered the field of further appraisal in a detailed discussion by H. P. BOARDMAN of the Nevada Cooperative Snow Surveys.

H. P. BOARDMAN (Nevada Cooperative Snow Surveys, Reno, Nevada)--There are good arguments for the use of the median method in determining a normal for precipitation or stream flow, but the inconsistencies in median values have about convinced me that the arguments against that method outweigh those for it in so far as snow surveys are concerned.

For instance the median value for annual flow of the Humboldt River at Palisade, Nevada, for a certain period of years considerably exceeds the sum of the 12 monthly medians for the same period of years. Likewise the median for a group of months as March to July does not check the sum of the five monthly medians for the same group. As a result, if one is watching the percentage of normal flow month by month as it develops through that period for a given year, one may form quite an erroneous impression of what one is to get in percentage of normal for the whole period March to July. On the other hand, if normals are determined by averages, the comparisons for different periods are consistent, that is, the sum of the monthly normals equals the normal for the group of months, for the whole year, or for a smaller group of months.

For the streams on the eastern slope of the Central Sierra, I have carried on some research towards developing a longer time-normal based on records of precipitation going back as far as 1870 for several stations on the western slope. For forecasting the runoff during April to July of the Truckee River the normal used since 1928 was the average for 24 years 1903-04 through 1926-27. Including the later years through 1940, and 1900-01 through 1902-03 lowers the average considerably, and if this 40-year average is raised to a 70-year period by comparison with the same 40-year period of western-slope precipitation, the normal is lowered still more. If medians are used instead of averages, the resulting normal in most cases is lowered below the arithmetic average.

In forecasting runoff we interpret the percentage of normal in terms of acre-feet, which is the useful unit for water distributors in irrigation and for power companies or other water users. So the value of the normal used is not all important as long as a change in runoff normal is accompanied by a proper change in snow-survey normals for the tributary basin. These normals represent arithmetic averages.

WALTER B. LANGBEIN (United States Geological Survey, Washington, D. C.)--In my opinion the heading "median versus mean" seems to imply some conflict between the two. This is not necessarily so, as much depends entirely on what is to be shown. The United States Geological Survey chose the median for use in Water Resources Review for the reason that it desired to emphasize comparisons with respect to time. That is, if the arithmetic mean were used, some streams, having extremely erratic regimens, chiefly those on the Great Plains, would be below "normal" over 90 per cent of the time. Obviously this repetitious condition would be illogical in a current report such as the Water Resources Review.

The United States Geological Survey generally uses the median only in connection with the Water Resources Review. In its annual Water-Supply Papers on the surface-water supply of the United States, the arithmetic average is used exclusively. The distinction is important. Here it is desired to report actual volumes (reported as mean rates) over specified periods of time, namely, the day, the month, the water year, and the period of record. The arithmetic average represents simply total volume during a specified period and is the only "average" that can be used for that purpose.

The fact that median values cannot be added or otherwise manipulated algebraically is, of course, a disadvantage. However, for the use BOARDMAN contemplates this again is not necessarily critical. In addition to reporting monthly discharges as percentages of corresponding medians the United States Geological Survey in the Water Resources Review compares the total runoff for cumulative periods of time with medians for corresponding periods. In other words, volumes of runoff for the period during October to March are compared with the median for that period, and so during the year. The person who is watching flow month by month can make his comparison just as readily that way as by reference to averages for the period and with the added advantage that information is given as to whether the flow has been exceeded more or less than 50 per cent of the time. The Water Resources Review publishes maps from time to time showing cumulative runoff with respect to medians for the same period.

BOARDMAN'S statement that "as a result, if you are watching the percentage of normal flow month by month as it develops through that period for a given year, you may form quite an erroneous impression of what you are to get in percentage of normal for the whole period March to July" can be true whether arithmetic averages or medians are used as normals. A group of percentages for partial periods cannot merely be averaged to get the percentage for the total period. The advantage that BOARDMAN cites seems only to relate to comparative ease of computation, not ease in use and interpretation.

As time and facilities permit, the United States Geological Survey is recasting for use in the Water Resources Review all medians to a standard base, namely, the 25-year period, 1921-45. For some representative stations this standardization results in dropping some of the early years, so far as the median is concerned, and for others, it requires extending records back to 1921. Extensions are being made by comparison with nearby long-term records or by rainfall-runoff relations. The period 1921-45 was not selected because of any special hydrologic quality, but rather for the practical reason that it represents the longest period of time for which records are generally common at the representative stations.

Shortening snow-survey courses--To cut down weariness and delay in snow surveying, it is important to reduce snow courses to lengths that still will give stable results. The cutting off of the ends of some courses has actually improved them by avoiding badly eroded or water-logged areas. The elimination of alternate measurements, if the snow is fairly uniform, will often yield the same total.

The following revision, described by H. P. BOARDMAN, was effected by rare good luck without change of normal: The revision of the Sonora Pass Snow Course has been effected without changing the value of the water-equivalent normal. This course is at altitude 8800 feet on the West Walker, one of the streams on the eastern slope of the Central Sierra. The original course was in two forks, the first having 27 samples and the other 13 samples, and it has been cut to 20 samples using numbers 2 to 11 of part one and 1 to 10 of part two. The records of 12 years were used, and the percentage relationship in water equivalent for each sample number to the value for the total 40 samples was tabulated for all of the 12 years. It was found that for the selected 20 samples the average varied from 97 to 105 per cent of the 40 sample values, one year giving 105 per cent, one year 97 per cent, one year 103 per cent, and the other nine years ranging from 99 per cent to 101 per cent. It is not likely that many snow courses will show as close a relationship when cut to one-half the original number of samples.

Effect of soil moisture on runoff

Normal precipitation during the period of snow-melt runoff has long been recognized as a major factor in maintaining the runoff at the percentage indicated by the snow. Normal precipitation during the autumn or normal soil moisture is now being considered essential to maintain the soil-priming loss at normal when the snow cover melts. This seems particularly true in the Pacific Northwest, where the normal precipitation in autumn is relatively heavy and drought would leave the soil dry. This would not apply, however, to the Great Basin, where the autumn is dry and dry soil is normal at the beginning of snow melt. This dry-autumn belt extends even to

the Sierra Nevada, but FRED PAGET [1946] has made out a strong case supporting this priming factor in improving accuracy of forecasts in the Kaweah Basin. For purposes of check a similar analysis of snow-cover and runoff data is planned for the neighboring Huntington Lake Basin. The soil mantle and precipitation in the two basins are similar.

The influence of the water table in the upper Humboldt Basin, Nevada, is a special case of saturation of the lowlands below the canyon mouths of the feeders and consequent inability of the basin to absorb its usual quota of runoff. The season of 1944-45 represents the combined influence of high water table and excessive precipitation during the runoff months of March-July. The snow cover on April 1 indicated a seasonal percentage of 115.4. The water table indicated a probable ten per cent additional, or a runoff at Palisade for March to July of 125 per cent. The precipitation for the period, however, was 181 per cent of normal as measured at the three precipitation stations of Elko, Wells, and Lamoille. The runoff was 247 per cent, or practically double the forecast. The data are shown in Table 2.

Table 2--Comparative data on precipitation and runoff, Humboldt Basin, 1945

Month	Precipitation	Temp. departure	Runoff at Palisade	
	Per cent of normal	(°F)	Per cent of normal	Normal ac-ft
March	163	- 4.8	136	32,600
April	88	- 5.7	195	47,200
May	222	- 1.0	305	54,500
June	338	- 6.6	257	60,400
July	117	+ 0.3	364	20,300
Average for period	181	- 3.6	247	215,000

Snow cover (Apr. 1), 115 per cent of normal; precipitation (Nov.-Mar.), 109 per cent of normal; snow cover + water table, 125 per cent of normal, equivalent to 268,750 acre-feet

The cold season and heavy precipitation, of which considerable at high elevations must have been in the form of snow, retarded and yet increased the runoff cumulatively toward the end of the season. The total was 532,260 acre-feet.

The snow cover and winter precipitation were almost identical (snow 115 per cent, precipitation 109 per cent). The present problem therefore is to separate the two factors of water table and precipitation during March to July and determine their powers. As a consequence of the heavy runoff, the water table must have been still further built up. The effectiveness of individual storms can be determined by the excess flow during the brief period, but excess flow during a longer period of continuous precipitation can not be so easily segregated. During the comparison one of the two factors should be normal.

Precipitation versus snow cover as basis for forecasting runoff

If melting in the meantime does not occur, the seasonal percentage of the accumulated precipitation should closely approximate that of the snow cover. Since percentages are sought based on normal trends, the harmony of the two should be sufficiently close for the use of either as a standard. The occasional capping of the gages or abnormal evaporation from the snow cover does not seem to be sufficiently frequent to distort the percentages greatly.

But if melting and loss should occur during the period of accumulation, only the residual snow-cover remains as a standard of estimate. The temperature even at the snowfields will scarcely indicate the loss by melting, for the depth, density, and temperature of the snow cover will be additional factors in determining the loss. Furthermore, the effect of winter melt on summer runoff still awaits detailed study and is complicated by the factor of soil priming.

South Yuba Basin--Three basins are available for comparative studies. Of these the South Yuba, California, has a long record using the station of Soda Springs for both precipitation and snow cover, and the station on the river at Lang's Crossing for stream flow. The entire period should be tabulated, but the last three seasons are presented in Table 3 as preliminary.

Table 3--Comparison of winter precipitation, snow cover, and runoff

Year	Soda Springs Precip. Nov.-Mar.	Soda Springs Snow cover Apr. 1	Soda Springs Precip. Apr.-July	Lang's Crossing Natural runoff Apr.-July
	per cent	per cent	per cent	per cent
1942-43	141.8	101	101.3	99.2
1943-44	62.0	68	171.9	73.3
1944-45	110.2	94	137.5	91.2
(Normals)	35.98 in	38.6 in	5.55 in	246,000 ac-ft

On the basis of the excess precipitation April to July, the runoff percentage should be fully as great as the snow cover. In 1942-43 the winter precipitation was far in excess of the snow cover but failed to raise the runoff above the percentage of the snow cover. On the other hand, the snow cover at Soda Springs (6750 feet) represented only the mean between the snow cover at high and low elevations on or near the watershed. For example, at the following stations at elevations indicated the percentages of normal were as follows: Lake Lucile, 8400 feet, 121; Webber Peak, 8000 feet, 112; Donner Summit, 7020 feet, 99; Soda Springs, 6750 feet, 101; and Lake Spaulding, 4900 feet, 31. This indicated a low early runoff on the lower reaches of the stream, a fully normal flow midway, and a high late runoff at the highest elevations. The water users were naturally alarmed at the bare foothills but were reassured by the snow measurements at the higher levels. The total flow for the season was 99.2 per cent, or approximately the percentage of the snow cover at Soda Springs.

On the basis of the zonal system worked out for the South Yuba Basin by the California Cooperative Snow Surveys the snow-cover percentage for the Basin was 90.0 per cent, still within ten per cent of the runoff but 50 per cent below the accumulated precipitation. The ten per cent excess of stream flow can well be the gain from the winter melting. The results are shown in Table 4.

Table 4--Results of zonal snow survey for South Yuba Basin

Altitude zones	Area	Per cent total Basin	Stations and snow cover			
Range in feet	sq. mi.	pct				pct normal
4500 - 6000	23.87	19.5	Lake Spaulding			31
6000 - 6800	37.06	30.4	Fordyce Lake		93	95.3
			Furnace Flat		92	
			Soda Springs		101	
6800 - 7500	44.50	36.4	Summit		99	109
			Sawmill Flat	100	105	
			Lake Sterling	107		
			Red Mt.	107		
			Meadow Lake		123	
Above 7500	16.71	13.7	Webber Peak			112
Total and weighted mean		100.0				90.0

In 1943-44, the runoff was larger than either the precipitation or the snow cover, particularly because of the heavy excess in precipitation during April to July. The correction factor for excess precipitation during runoff has not yet been determined, but the precipitation percentage (November to March) should not have been lower than that of the snow cover (April 1).

In 1944-45, there was a difference of 16 per cent between the two with the percentage of runoff approximating that of the snow even with some excess during April to July in precipitation.

A long comparison of precipitation and snow cover in the Tuolumne River Basin by H. P. BOARDMAN indicates that "as a basis for forecasting stream flow in this basin the advantage appears to be decidedly with snow surveying."

Discussion--The suggestion has been made that the data presented for the South Yuba Basin are based only on three years of record, although the normal upon which the percentage is based represents the arithmetical average or mean of 14 years of record. To make the analysis as complete as possible, it was finally decided to expand the comparison to cover the entire period, which has been done in the following statistical analyses by H. LANDSBERG and F. B. HEADLEY (Chief of Farm Development, Nevada Agricultural Experiment Station).

H. LANDSBERG (University of Chicago, Chicago, Illinois)--Forecasting of runoff in South Yuba River Basin from precipitation and snow-survey data: A statistical analysis. The problem presented is to compare the reliability of forecasts of runoff in the South Yuba River obtained from snow-survey and precipitation observations. Available for analysis were 14 years, from 1932 through 1945. The basic data are covered in Table 5. Column (2) of that Table shows the precipitation at Soda Springs, one of the precipitation stations in the drainage area, from August through October of the preceding year, in per cent of the normal for that station; the significance of the column is supposed to be that of a "priming factor" for the subsequent runoff season. Column (3) gives the total precipitation, in per cent of normal, from November through March for Lake Spaulding, the other available precipitation station in the drainage area; this is the main amount of precipitation available for runoff. Column (4) gives the same quantity as Column (3) for Soda Springs. Column (5) is total precipitation in per cent of normal, from April to July for Soda Springs. Columns (6) and (7) show the precipitation for Soda Springs and Lake Spaulding for April and May, expressed as per cent of the total post-snow season precipitation, April through July; these two months represent the most important portion of precipitation available, outside of the essential amount falling during the snow season proper. Column (8) gives the water content of the snow on the ground on April 1 at Soda Springs as established by snow surveys, in per cent of normal. Column (9) finally shows the runoff in the South Yuba River, in per cent of normal. It is considered that the accuracy of the figures in this Column is probably not better than ± 10 per cent and certainly not more accurate than ± 5 per cent.

Table 5--Data for the forecasting of runoff, South Yuba Basin, California

Year (1)	Precipitation						Snow cover April 1, Soda Springs (8)	Runoff April-July South Yuba River (9)
	Aug.-Oct. Soda Springs (2)	November-March		Apr.-July Soda Springs (5)	April-May			
		Lake Spaulding (3)	Soda Springs (4)		Soda Springs (6)	Lake Spaulding (7)		
	pct	pct	pct	pct	pct[a]	pct[a]	pct	pct
1932	152	91	105	162	148	146	111	126
1933	22	61	70	127	124	112	84	82
1934	224	60	63	116	55	46	39	32
1935	118	91	88	232	232	178	118	130
1936	97	118	106	143	74	65	122	126
1937	54	83	82	103	65	59	115	108
1938	93	141	156	97	69	70	162	161
1939	125	56	51	52	50	66	55	42
1940	180	152	149	69	65	58	111	93
1941	92	136	115	191	156	151	107	115
1942	62	127	122	208	204	221	99	121
1943	37	140	133	101	71	71	102	100
1944	78	71	58	172	122	79	68	74
1945	129	96	103	138	105	86	94	91
Normal	3.40 in	50.36 in	35.98 in	5.55 in			38.6 in	246,000 ac-ft

[a] Of April-July normal.

The question arises: How, with the data as given in Table 5, could a forecast of runoff during April to July for the South Yuba River have been given with the greatest reliability? Prior to the establishment of snow surveys the only possibility would have been the use of the observations of precipitation at Lake Spaulding or at Soda Springs, or at both of these stations. Had, for example, the winter precipitation at both Soda Springs and Lake Spaulding been combined to give a mean percentage [Columns (3) and (4) divided by two], the runoff figures given in Column (2) (noted as deviations of actual runoff) of Table 6 would have been obtained. This would have resulted in a mean absolute error of 23 per cent, and a maximum error of 58 per cent in those 14 years would have been made. Had precipitation at Soda Springs alone been used, the deviation figures against the observed value given in Column (3) of Table 6 would have been the result. This station alone would have given a better forecast, although the mean error would still have been 20 per cent, and the maximum error 56 per cent.

It can be argued that the precipitation during the post-snow season, at least for April and May, should have been entered into the forecast. This was done by correcting the percentage values in Columns (2) and (3) of Table 6 with a factor of one-fifth of the percentage deviation of the precipitation during April and May from normal precipitation during the post-snow season. The factor one-fifth was entered because it represents the approximate relative value of the precipitation during the post-snow season compared to the precipitation in the main snow season, November through March. The corrected values appear in Columns (4) and (5) of Table 6. The values given indicate that the correction results in an improvement of the potential forecasts. The mean error for the combined stations still remains, however, 22 per cent, the absolute highest error 50 per cent. For Soda Springs alone the errors would be in the mean 19 per cent, in the maximum 48 per cent. In both cases the correction would have improved eight forecasts, would not have changed one forecast, and would have worsened five forecasts.

A method now favored by many is to use the snow-survey data for forecasting of the runoff in the post-snow season. The deviations from the observed runoff in the South Yuba River for a forecast based solely on the snow-survey data of April 1 at Soda Springs is shown in Column 6 of Table 6. The mean error of that type of forecast is nine per cent, the maximum 22 per cent. This in itself would have been more reliable than the forecast based on the two precipitation stations.

The same correction that was applied to the precipitation data for post-snow season in April and May was also applied to the snow-survey data with results as shown in Column (7) of Table 6. By this procedure the mean error was cut down to only five per cent and the maximum error to ten per cent. Both these figures are within the error range of the runoff observations. The application of the correction for precipitation during the post-snow season resulted in an improvement of nine forecasts, no change in one case, and worsening, although by only small amounts, in four cases.

Table 6--Percentage deviation of runoff forecast compared to observed value, based on various methods

Year	Basis of forecast					
	Precip., Lake Spaulding and Soda Springs Nov.-Mar./2	Precip., Soda Springs Nov.-Mar.	Column 2 corrected by 1/5 precip., Apr.-May	Column 3 corrected by 1/5 precip., Apr.-May	Soda Springs snow April 1	Column 6 corrected as columns 4-5
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	pct	pct	pct	pct	pct	pct
1932	- 28	- 21	- 19	- 12	- 15	- 6
1933	- 16	- 12	- 12	- 8	+ 2	+ 4
1934	- 30	+ 31	+ 20	+ 21	+ 7	- 3
1935	- 40	- 42	- 20	- 22	- 12	+ 10
1936	- 14	- 20	- 20	- 26	- 4	- 10
1937	- 26	- 26	- 34	- 34	+ 7	- 1
1938	- 12	- 5	- 18	- 11	+ 1	- 5
1939	+ 12	+ 9	+ 4	+ 1	+ 13	+ 5
1940	+ 58	+ 56	+ 50	+ 48	+ 18	+ 10
1941	+ 32	0	+ 42	+ 11	- 8	+ 3
1942	+ 4	+ 1	+ 25	+ 22	- 22	0
1943	+ 37	+ 33	+ 31	+ 27	+ 2	- 4
1944	- 9	- 16	- 9	- 16	- 6	- 6
1945	+ 9	+ 12	+ 8	+ 11	+ 3	+ 1
Mean absolute error	23	20	22	19	9	5
Max. error	58	56	50	48	22	10

The foregoing discussion raises the question why the precipitation data by themselves furnish such unreliable clues regarding the runoff in the river. It is believed that the answer to that problem is the same as in many other cases where measurements of precipitation furnish only very general trends regarding the hydrologic balance. And that is the imperfect sampling technique of current measurements of precipitation. It would be rather surprising, knowing the heterogeneity of precipitation in a storm, especially in mountainous country, if a small can, only eight inches in diameter, could furnish an adequate picture of the water that has fallen over many square miles of territory. In addition, there is the difficulty, discussed many times, of measuring solid precipitation reliably by means of the ordinary rain gage.

In the case under discussion, the mean deviation of the precipitation (in terms of the normals), measured at Soda Springs and Lake Spaulding, was eight per cent for the period from November through March and in the year of maximal difference between the two stations it was 21 per cent of the respective normals. During the post-snow season, April to May, the mean deviation between the two gages was 15 per cent of the normals with a maximum of 64 per cent. With only two rainfall stations available it would be hard to decide how to apportion properly the measured precipitation over the watershed. Experience elsewhere suggests that many more rain gages would be needed, even in a small watershed, to get a better approximation of total amounts fallen.

A special word ought to be devoted to the priming factor. In the case of the South Yuba River the precipitation observed from August through October furnishes only a small proportion of the annual precipitation, and the shallowness of the superficial water-holding layer diminishes this influence even more. Every attempt to obtain in this watershed a significant factor from the precipitation during the pre-snow season failed. The values scatter almost at random and in no way could a consistent correction be obtained from the values of precipitation during August to October for the 14 years investigated. It seemed better to disregard this factor completely. This result is, of course, not immediately applicable to other watersheds where hydrologic and geologic conditions may (and are known to) raise the significance of the priming factor.

Another very important factor regarding the reliability of the snow-survey data is the time of the survey. Especially in years of excessive precipitation it is absolutely essential to reduce the snow-survey data to the key day of the survey, say April 1. For example, in 1935 the snow survey in the South Yuba Basin was not made until April 9. In the first nine days of April a considerable amount of precipitation fell (about ten inches at Lake Spaulding and eight inches at Soda Springs). This amount of precipitation was absorbed in the snow cover so that the survey on April 9 contained a much greater water equivalent than would have been the case had it been made on April 1. The error in this case, had no reduction been made to the date April 1, would have amounted to 21 per cent of the normal, and the snow survey would have given runoff figures too high by that amount had not the precipitation amount from April 1-9 been subtracted from the actual snow-survey values. In Table 5 the snow-survey figures have been appropriately corrected. This indicates how essential it is to make snow surveys on the key date or at least make the proper allowances if weather conditions necessitate a delay or advance in the date of the survey.

The conclusion from the analysis of the above data is that for the South Yuba River the snow-survey data on April 1 from Soda Springs allow a reasonable forecast of runoff during April to July with an error of normally less than ten per cent. This forecast is superior to one that could have been obtained from the observations of precipitation at either Soda Springs or Lake Spaulding, or both, from November through March. A correction applied for precipitation fallen during April and May to the snow-survey data would improve the forecasts of runoff. Application of a similar correction to the observations of precipitation would have reduced the mean error of a runoff forecast, based on these observations, only to 19 per cent. The frequency distribution of deviations of potential forecasts by the various methods compared to observed runoff is given in summary in Table 7.

"Fundamentally," LANDSBERG adds further, "regression equations are generally more applicable to natural phenomena. The results for the South Yuba, however, show that for snowfall this method is not necessary, and that forecasts can be made within the limits of the desired accuracy without resorting to a more elaborate technique."

F. B. HEADLEY (Nevada Agricultural Experiment Station, Reno, Nevada)--Use of correlation curves in comparison of snow cover and precipitation on the South Yuba; I am enclosing charts for the South Yuba River Basin showing geographically the relation (a) between the runoff from April to July at Lang's Crossing, and precipitation during the previous months, November through March at Soda Springs (see Fig. 2) and between runoff as in (a) and snow cover at Soda Springs on April 1 (see Fig. 3). This is for data obtained during the years 1932 to 1945

(Table 8). It can be seen at a glance that precipitation data could not well be used for forecasting runoff. On the other hand, estimates based on snow cover are quite accurate as shown in Table 8. The regression equation is Y = (- 7.2 + 1.083X), which means that if one multiplies the snow cover by 1.083 and subtracts 7.2 one has a fairly good estimate of the runoff in per cent of normal. It would probably be preferable to prepare an equation using snow-cover and runoff figures without first changing them to per cent of normal.

Table 7--Frequency distribution of deviations of potential forecasts by various methods

Forecast method	No. of cases with error from			
	0 - 10	10 - 20	21 - 30	31 or more
	pct	pct	pct	pct
Precipitation November to March				
Soda Springs and Lake Spaulding combined	3	4	3	4
Soda Springs alone	4	4	2	4
Soda Springs-Lake Spaulding, corrected for precipitation during April and May	3	6	1	4
Soda Springs, corrected for precipitation during April and May	2	5	5	2
Snow Survey, April 1				
Soda Springs	9	4	1	0
Soda Springs, corrected for precipitation during April and May	14	0	0	0

Further comment by J. E. CHURCH--Since both precipitation and snow cover are measured in terms of inches of water equivalent, they should be comparable without reduction to per cent of normal. The percentage system, however, makes possible the application of the departure of precipitation during April to correcting the forecast on May 1. Furthermore, the percentage system is the only means of comparing the rise of lakes and the flow of streams.

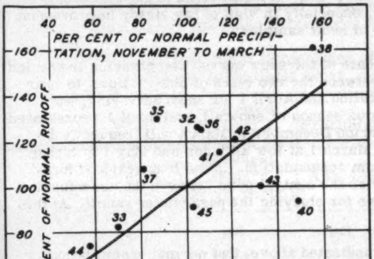

Fig. 2--Relation of per cent normal runoff to per cent normal precipitation, South Yuba Basin, California, 1932-1945 (variation of one per cent in precipitation caused variation of 0.735 per cent in runoff; chart uncorrected for April-May precipitation)

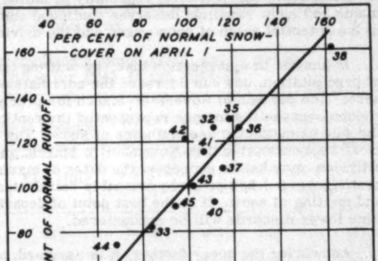

Fig. 3--Relation of per cent normal runoff to per cent normal snow cover, South Yuba Basin, California, 1932-1945 (variation of one per cent in snow cover caused variation of 1.083 per cent in runoff; chart uncorrected for April-May precipitation)

Table 8--Snow cover at Soda Springs and runoff at Lang's Crossing in per cent of normal

Year	Snow cover April 1	Estimate, Y = (- 7.2 + 1.083X)	Runoff April-July	Error of estimate[a]
	pct	pct	pct	pct
1932	111	113	126	- 13
1933	84	84	82	+ 2
1934	39	35	32	+ 3
1935	118	121	130	- 9
1936	122	125	126	- 1
1937	115	116	108	+ 8
1938	162	168	161	+ 7
1939	55	52	42	+ 10
1940	111	113	93	+ 20
1941	107	109	115	- 6
1942	99	100	121	- 21
1943	102	103	100	+ 3
1944	68	75	74	+ 1
1945	94	95	91	+ 4

[a] Uncorrected for precipitation during April and May.

Regarding my statement that precipitation percentage should not have been lower than that of the snow cover, under ideal circumstances of no melting occurring during November to March, the accumulated precipitation (if all is caught) should be in excess of the accumulated snow cover measured at the same place, for the latter would have been subjected to long periods of evaporation, but since the use of normals absorbs this loss, the percentage should remain unaffected. Since, moreover, the measurements of precipitation are unaffected by melting in November or other times during the winter, while the snow cover would suffer resultant decrease, the percentage of the precipitation should equal or exceed that of the snow cover, which at best is only a residue. It is admitted, however, that wind, snow caps, and lack of gage capacity may reduce the measurements considerably, especially of falling snow. The variation between gage measurements and snow sampling deserves continued study, especially in view of the steady improvement in the potential catch of snow gages and the driving of snow samplers.

In answer to a suggestion that "by shifting the date of the snow survey and changing the period of precipitation, one can decrease the correlation between the two types of observations to near zero," the periods of November-March for precipitation and April 1 for snow surveying, were chosen because the former represented the continuous season of snowfall, and April 1 represented the date of maximum accumulation of snow. The period December to March will frequently be more representative than November to March, and March 1 at low altitudes and May 1 at higher altitudes, may better represent the dates of maximum accumulation. In the long years of forecasting, April 1 has proved reasonably satisfactory as the central point between the accumulation and melting of snow. It is the best point of departure for studying the post-winter runoff. At this time fewer discords will be encountered.

Answering the query further, it is assumed, as indicated above, that normal precipitation during November to March will mean normal snow cover on April 1 unless winter melting has caused loss. Only snow surveying will indicate this conclusively.

The low courses, like the high courses, indicate the percentage of normal snow present in their respective altitude zones. Care is taken to avoid locations where the ground may become bare at the dates of snow surveying, for all index of accumulation or melting would be lost. The presence of bare ground does not indicate complete lack of precipitation but low precipitation or excessive melting. The use of the percentage system duly weighted indicates the general condition of the area.

Columbia River Basin above The Dalles, Oregon--The Columbia Basin has long been the center of forecasters' conferences to estimate the seasonal runoff of its streams and the prospects for all needs of power, irrigation, and navigation, as well as flood prevention. A similar conference has now been organized in the Colorado Basin for the better regulation of Boulder Dam.

Snow surveys have been carried on for ten years, and for two years estimates have been based on precipitation plus temperature. The forecasts issued by the Division of Irrigation of the United States Soil Conservation Service and the United States Weather Bureau have, however, not been readily comparable mainly because of diversity in the periods of normals and the length of the runoff season.

For example, the snow-survey percentages are based on only ten years of record and the precipitation percentages on approximately 20 years. Furthermore, the snow-survey estimates of runoff are for April to September, whereas the precipitation-temperature estimates are for April-July. Finally, the normal of stream flow near The Dalles is based for the snow surveys on 66 years of record but for precipitation temperature on only 20 years, chosen because this shorter period parallels many of the records of precipitation with which it must be compared. The longer normal considerably exceeds the shorter, the two normals for April to July being 70,700,000 acre-feet (1925-1944, 20 years) and 84,800,000 acre-feet (1878-1944, 67 years). The latter is 20 per cent larger. These data were provided by the United States Geological Survey, Portland, Oregon. The ten-year normal, later received, is 67,402,000 acre-feet, only five per cent smaller than the 20-year normal. Therefore the use of the 20-year runoff normal with the ten year snow-cover normal should yield fairly close forecasts. Because of lack of accessible data, the snow-survey forecasts had used a 66-year cumulative normal.

Comparison of the two methods should preferably be based on the 20-year normal of runoff and accumulated precipitation, and the ten-year normal on snow cover and runoff for similar periods as April to July, the months in which the bulk of the runoff occurs.

Since the precipitation percentage has been weighted by concurrent temperature, and the snow-cover percentage has been modified to correspond with the runoff-percentage of similar seasons, the precipitation and snow cover will be compared directly on the basis of their own normals without weighting or adjustment.

In view of the lack of weighted percentages of precipitation for the contribution by the various main feeders, the average for the various areas as given in the Snow Survey Forecast (by the Division of Irrigation) will be used, and the snow-survey percentages will be weighted according to the following values of estimated contribution (in per cent) by the sub-watersheds to the main stream near The Dalles: Upper Columbia-Kootenay, 47; Clark Fork, 13; Clearwater, 8; Salmon, 6; Snake (above Clearwater and Salmon), 6; and other tributaries, 20--a total of 100 per cent. On this basis, Table 9 of comparative percentages has been prepared.

Table 9--Comparison of percentages of precipitation, snow cover, and of runoff in the Columbia Basin above The Dalles for 1943-44 and 1944-45

Season	Precipitation accumulated Nov.-Mar. (20-yr. norm.)	Snow cover on April 1 weighted for principal feeders (10-yr. norm.)	Precipitation at Spokane		Runoff near The Dalles Apr.-July (20-yr. norm. 70,700,000 ac-ft)		Peak flow at Celilo Falls near The Dalles (normal 490,000 cfs on June 8)	
			Aug.-Oct.	Apr.-July				
	pct	pct	pct	pct	ac-ft	pct	cfs	pct
1943-44	68.2	79.3	159.6[a]	81.0	44,448,000	62.9	324,400 (June 19)	66.2
1944-45	81.7	105.8	76.6	103.8	65,429,000	92.5	508,000 (June 8)	103.7

[a] Average of seven stations, Cle Elum, Lake Keechelus, Lake Wenatchee, Okanagan, Pullman, Yakima, Spokane, 102.3 per cent.

The Weather Bureau has suggested using the following values: Upper Columbia 40 per cent; Snake 28 per cent; and other feeders 32 per cent. It also has 75 key precipitation and temperature stations upon which its estimates are based. The data from these, if available, should be used. Potential forecasts as compared with actual flow, in terms of percentage of normal, are shown in Table 10.

Table 10--Forecasted runoff near The Dalles, in percentages of normal

Season	U. S. Weather Bureau, forecast based on precipitation and temperature	Div. of Irrig., U. S. Soil Conservation Service, forecast based on snow cover and adjustment	Actual runoff	Peak flow by U. S. Weather Bureau only and date	Actual peak and date
	pct	pct	pct	pct	pct
1943-44	58.6	63.2	62.9	58.2, June 1-7	66.2, June 19
1944-45	68.0	72.8	92.5	71.0, June 18	103.7, June 8

It will be noted that the above forecasts (Table 10) are based on precipitation modified by temperature and on the snow cover adjusted to comparable years. This fortunately provided close forecasts in 1943-44 but fell far short in 1944-45. The unmodified precipitation and the snow cover computed simply in terms of normal (Table 9) appear to give more dependable estimates.

The precipitation is in all cases less in percentage than the snow cover, although the reverse should be true. Would the use of the 75 stations weighted according to the contribution of the various areas in the basin correct this? Parallel normals for precipitation and snow cover might aid if only the snow-cover series were 20 years long. The precipitation before snowfall and during snow melt does not depart sufficiently below normal to account fully for the fall in percentage of the runoff below the snow cover but may account for some.

The peak flow is almost wholly the result of snow melt and should be approximately proportionate to the amount of the snow cover. Its date will be controlled largely by temperature. In 1943-44 the date was delayed, and the crest was somewhat lower than the indication of the snow cover. In 1944-45, with normal date, the percentages of snow cover and peak flow were close.

G. H. CANFIELD (U. S. Geological Survey, Portland, Oregon)--This is with reference to your letter of October 20 and the accompanying copy of draft of Report of the Research Committee of the Western Snow Conference.

In the last paragraph of your letter of October 20 you inquired if you were right in assuming that the percentage of snow cover in 1945 is closer to the percentage of the peak flow than any of the other estimates. Your assumption is correct. You show for April 1, 1945, snow-water storage 105.8 per cent of the ten-year normal for the Columbia River Basin and the June 1, 1945, peak flow of the Columbia River at The Dalles as 103.7 per cent of a 20-year normal or average annual peak of 490,000 cfs. The peak flow in 1945 was 508,000 cfs. I note that this comparison did not work out so well for the peak discharge of 1944. Many systems of long-range forecasting of the annual peak discharge of the Columbia River near The Dalles have been brought forth in the past, most of which, according to their authors, give excellent results when applied to records of the past; however, when applied to events to come they seem frequently to fall down. In my opinion, the runoff April to July or April to September for the Columbia River near The Dalles generally can be forecast closely by antecedent precipitation or snow-water storage on April 1; also the probable peak discharge within a range of 25 per cent, sufficient to give some warning two months in advance as to the magnitude of the peak stage of the lower Columbia River to be guarded against. However, the peak stage and discharge are greatly affected by temperature and precipitation during April, May, and June. If the snow is melted slowly, peak will be lower; but if the melting is accelerated by extremely hot period in late May and early June, the discharge may reach a peak much higher than forecast in April.

The United States Weather Bureau at Portland has been issuing daily bulletins during the period April to June, giving stages of Columbia River at stations upstream as far as British Columbia, and on the Snake River, on which are based forecasts of probable stage in the Vancouver and Portland harbors. The long-range forecast in April gives a general idea as to whether the peak stage of the Columbia River will be relatively high or low, and the subsequent daily forecasts of the Weather Bureau begin to tie the time and magnitude of the peak down to rather close limits a few days in advance.

After any system of long-range forecasting of the peak stage and discharge of the Columbia River has proved to be within ten per cent for four out of five years, then I believe we may begin to give more credence to the method and the long-range forecast. But I do not expect it until there is a reliable system for forecasting the weather two months in advance.

Colorado River Basin--The forecast problems of the Columbia and Colorado Rivers are widely diverse, for the Columbia traverses a storm belt with increasing precipitation toward its mouth, while the Colorado enters a rainless belt and receives, with the exception of the intermittent Gila, little accretion downstream.

The Columbia exceeds the Colorado in volume nine fold (151,710,000 acre-feet at The Dalles as compared with 17,489,000 acre-feet at Yuma). The Columbia therefore has far more water than can be utilized on available irrigable land, whereas the Colorado is far overburdened with land to serve. Consequently, forecasting of the Colorado water supply has become an earnest and delicate task.

Fortunately, as compensation for its desert area, the Colorado's watershed of 225,000 square miles is reduced, for purposes of forecast, by almost one-half and the crest line of 760 miles is diminished to 330 miles.

Furthermore, three tributaries, the Green (5,797,760 acre-feet), the Upper Colorado (6,650,200 acre-feet), and the San Juan (2,745,270 acre-feet) furnish 87.1 per cent of the mean annual runoff at Yuma. Moreover, their runoff during April to July attains 67.0 to 75.0 per cent of the annual, thus establishing their snow-fed character.

The task of forecasting the runoff of the Colorado is one of concentration on the three main feeders mentioned. To understand these better, an atlas of the percentage harmonics of all of the contributors of the Colorado is being prepared at the suggestion of F. C. MERRIELL, and much of the work on the Upper Colorado has been completed.

Since 1936, precipitation gages have been used by the United States Bureau of Reclamation to parallel the snow-survey courses for the study of the relative accuracy of the two methods of forecasting. A table was recently published [RITER, 1944] comparing forecasts of 1943, based on snow measurements and on cumulative precipitation, with actual flood-season runoff.

The accuracy of prediction on February 1 and March 1, 1943, was the same with both snow cover and precipitation, but the comparison showed that as of April 1 and May 1 the forecast based on precipitation became close whereas the inaccuracy for the forecasts based on snow cover became extreme.

Since war restrictions have been relaxed, the following report for 1944 has been generously provided with accompanying comments.

Bureau of Reclamation--The Bureau of Reclamation makes predictions, early in February, March, April, and May, of the subsequent inflow through July to Lake Mead. Predictions are based both upon snow measurements made on the first of each of these successive months, and upon cumulative precipitation subsequent to September 30 of the previous year. By correlation of past observed snow pack and subsequent flood-season runoff, the Bureau attempts to forecast minimum probable, mean probable, and maximum probable flood-season inflow to Lake Mead. The results of the predictions for 1944 based upon snow measurements and the results of parallel forecasts based on cumulative precipitation subsequent to September 30, 1944, are shown in Table 11. At no time during 1944 was there a prospect of flood runoff greater than that which could be handled in routine operation. No water was released from Lake Mead during 1944 solely for flood-control purposes. Total capacity of Lake Mead to the top of spillway gates is 31,140,000 acre-feet.

In 1944, the inaccuracy of forecasts based on snow cover and precipitation was similarly high for both until May 1, at which time forecast based on the snow cover was accurate within ten per cent, but the inaccuracy of the forecast based on precipitation continued.

These "Lake Mead forecasts" seemed so obviously affected by readjusted normals that the data on snow cover accumulated for ten years with data on precipitation and stream flow have been analyzed after the manner of the Nevada forecasts. When revised as of May 1, every forecast on the basis of snow cover on April 1 fell within 15 per cent of normal of that of the runoff of the Colorado River April to July near Bright Angel Creek, above Lake Mead. The percentage indicated by the precipitation was sometimes closer but usually farther away. Its maximum deviation was 40 per cent. In view of the relatively heavy precipitation after May 1, the maximum limit of error of 15 per cent of normal on May 1 was wholly unexpected.

Table 11--Joint forecast based on snow cover and precipitation, Colorado River Basin, by the United States Bureau of Reclamation, 1944

Date of forecast	Runoff period covered	Actual runoff[a]	Runoff forecast based on snow-cover measurements				Runoff forecast based on precipitation measurements			
			Minimum probable	Mean probable	Maximum probable	Deviation in mean probable	Minimum probable	Mean probable	Maximum probable	Deviation in mean probable
		M ac-ft[b]	M ac-ft[b]	M ac-ft[b]	M ac-ft[b]	pct	M ac-ft[b]	M ac-ft[b]	M ac-ft[b]	pct
Feb. 1, 1944	Feb.-July	11,250	5,400	8,000	11,500	- 29	5,200	8,100	10,800	- 28
Mar. 1, 1944	Mar.-July	10,890	4,400	7,000	10,500	- 36	4,700	7,400	10,200	- 32
Apr. 1, 1944	Apr.-July	10,330	6,250	8,300	12,100	- 20	5,000	7,800	10,750	- 24
May 1, 1944	May-July	9,230	7,250	10,000	11,600	+ 8	4,750	7,250	9,750	- 21

[a] Preliminary, subject to revision.

[b] M ac-ft is thousands of acre-feet.

Table 12--Comparison of percentages of normal precipitation (October to March) and snow cover (April 1) with percentage of normal runoff, April to July, Colorado River Basin (uncorrected)

Item	Normal	Year									
		1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
Precipitation, October-March, inch	5.8[a] 6.46	73.0[a]	105.2[a]	118.5[a]	104.0	90.9	133.8	132.2	110.9	92.0	96.7
Snow cover, April 1, inch water equiv.	14.9	118.8[b]	109.4	113.4	83.5	71.0	99.8	98.4	106.1	95.6	102.0
Snow cover, May 1, inch water equiv.	12.0	126.3[b]	89.2	105.9	100.4	105.3	148.4	104.1	55.7	121.8	131.1
Precipitation for April	1.1[a] 1.3	40.1[a]	31.2[a]	96.5[a]	53.6	124.2	219.8	172.9	51.4	133.7	90.3
Temp.-departure for April (Grand Junction), °F	52.4	+ 2.8[c]	- 1.7[c]	+ 0.8[c]	+ 3.2[c]	+ 2.0[c]	- 3.2[c]	+ 1.8[c]	+ 7.9[c]	- 4.4[c]	- 4.6[c]
Runoff of Colorado River, April-July, at Bright Angel Creek,	9,006,000 ac-ft	96.0	97.8	125.0	63.9	51.4	133.7	127.8	85.6	114.4	90.2
Variation between precipitation and runoff	. . .	-23.0	+ 7.4	- 6.5	+40.1	+39.5	+ 0.1	+ 4.4	+25.3	-22.4	+ 6.5
Variation between snow cover and runoff	. . .	+22.8[b]	+11.6	-11.6	+19.6	+19.0	-33.9	-29.4	+20.5	-18.8	+11.8

[a] Represented only by Green River, Grand Junction, and Durango for the Green, Colorado above Palisade, and San Juan River Basins, respectively.

[b] Incomplete.

[c] Deviation from normal in °F.

In the case of large and complex basins such as the Colorado and the Columbia the harmonics of precipitation, snow cover, and runoff should be studied for the main stream and larger feeders. Data should be weighted by altitude zones as well as by relative contribution of subordinate areas to the total watershed. Search should be made for individual differences as a means of identifying and computing the factors bearing on runoff.

The present analysis, however, covers only the precipitation and snow cover weighted by relative contribution of areas or feeders and the runoff of the Colorado at Bright Angel Creek near Grand Canyon, 267 miles upstream from Boulder Dam. The data for runoff have been expedited by the United States Bureau of Reclamation and the United States Geological Survey. The averages for snow cover and precipitation have been taken unmodified from the "Snow surveys and irrigation water forecasts for the Colorado River Drainage Basin" by the Division of Irrigation, United States Soil Conservation Service. Table 12, showing precipitation, snow cover, and runoff is based on the principles of forecasting gradually developed by the Nevada Agricultural Experiment Station and used in the earlier analysis in this Research Report. Some principles may bear repeating:

(1) The major factor in the summer (April-July) runoff is the snow cover, which attains its maximum accumulation about April 1. Since the snow begins to melt steadily by April 1, the basic normal for computing percentage of the summer flow must be the snow cover on April 1 and not the snow residue on May 1. Any later readjustment in the forecast, as on May 1, must be a modification in the forecast of April 1 owing to departure from normal of the precipitation during the interval, as for example during April. The difference in the snow cover on May 1 from that on April 1 should be a combination of precipitation and temperature effect during April and may therefore differ considerably from the precipitation alone.

(2) The percentage of the precipitation during October to March or preferably November to March under ideal conditions of gage catch should correspond to the percentage of the snow cover providing winter melting has not occurred.

(3) The effect of soil moisture in the autumn probably is small as in the Sierra Nevada watersheds because of the steepness of much of the slope, but should nonetheless be determined where possible. Departure from normal temperature during this period still appears to have little if any effect on the total runoff, though obviously it does retard or accelerate it. There is finally the effect of diversions above points of stream gaging when the flow is considerably above or below normal. There may also be the effect of high or low water table on the total flow, but because of the steep gradient this can in no wise resemble that of the Humboldt Basin, Nevada.

(4) Since the accuracy of early or long-period forecasts is being discussed, only one revision, May 1, is proposed, although a second revision on June 1 would be closer to the actual since by this time approximately 40 per cent of the flow during April to July has occurred.

Table 12 presents data weighted but uncorrected, and the comparison is confined to April 1. Table 15, however, contains all available correction factors for both April 1 and May 1 and comparisons for both dates. The details precede the Table.

Details regarding data, Colorado Basin--The means for precipitation and snow cover were obtained from the annual Reports of Snow Surveys of the Colorado Basin, and the weights for relative contribution of water by the constituent areas were provided by the United States Bureau of Reclamation. No attempt has yet been made to segregate the precipitation and snow-survey stations by altitude in order to use altitude zones in addition to the relative areas of the principal tributaries. The normals for precipitation were derived from United States Weather Bureau departures based on period of record. Those for snow cover and runoff are based fortunately on the same period, ten years, representing the extent of the snow surveys. The temperature departure, provided by the United States Weather Bureau, represents the period of record.

The weighting of the precipitation by tributaries is less detailed than in the case of the snow cover, but the consequent error seems small. In the former case, only the Green River (10 per cent), Colorado above Palisade (25 per cent), and the San Juan (17 per cent), in total 52 per cent, are used, while in the latter, the Green (10 per cent), Yampa-White (16.5 per cent), Colorado above Palisade (25 per cent), Gunnison (15 per cent), San Juan (17 per cent), and Dolores (7 per cent), in total 90.5 per cent, were used. Since the Yampa-White, Colorado above Palisade, and Gunnison are topographically one unit, as are the San Juan and Dolores, the weights for precipitation are practically: Green, 10 per cent; Upper Colorado, 56.5 per cent; and San Juan, 24 per cent (total 90.5 per cent). Two tests, for example 1936 and 1941, revealed only minor differences between these weights:

In 1936, using the total weight of 52 per cent, the value in terms of the normal came out 104 per cent, while using a total weight of 90.5 per cent the value became 106 per cent. In 1941, using the total weight of 52 per cent, the value in terms of the normal came out 133.8 per cent, while using a total weight of 90.5 per cent, the value became 131.3 per cent. For the present analysis, therefore, a more detailed segregation of records of precipitation will not be attempted. The progress in the development of high-altitude precipitation stations is indicated in the following:

C. B. JACOBSON (Acting Chief, Hydrology Division, Bureau of Reclamation)--Following the plan proposed by **DEBLER** and **JOHNSON**, several high-altitude precipitation stations were established, 22 of which are now in operation, and of this number, 21 have ten years of record. Although the records are not of sufficient length to enable a detailed statistical analysis, it is expected they will, after a few more years, be of considerable value in forecasting runoff. These data have not been published. It is felt that a statistical analysis should precede the publication and general application of these records. Of the series of snow courses proposed in "Forecasting Colorado River runoff," to which you have referred, only a few, located and named as in the proposed series, are in operation. All courses employed in our forecasting procedure are included in the list prepared by **PARSHALL** and published by the United States Soil Conservation Service.

Accuracy of forecasting on April 1, Colorado Basin--As already mentioned, the relatively heavy precipitation on the Upper Colorado during April to July as compared with December to March (the period of accumulation) subjects the runoff period of April to July to the possibility of great divergence from the percentage indicated by the snow storage on April 1. The disproportion between the seasonal precipitation in the Sierra Nevada and Continental Divide is extreme. In the Sierra Nevada, the precipitation during December to March is 67.41 inches compared to an April to July normal of 15.17 inches, while on the Continental Divide the corresponding normals are 28.83 and 31.00 inches. It is, therefore, a source of high satisfaction to find that in eight years out of ten, the snow cover on April 1 with obvious corrections that can be made at that time is within a maximum deviation of approximately 20 per cent of the runoff from April to July. This compares roughly with ten per cent in the Sierra Nevada. The remaining divergent years can be detected at the adjusted forecast of May 1.

Available correction factors, Colorado Basin--The correction factors available as of April 1 for modifying the percentage of precipitation or snow cover are (1) autumn priming before snowfall, (2) the height of the water table at the beginning of major runoff (April to July), (3) the disproportionate melting of the snow cover in the lower zone of the watershed in the winter, and (4) the effect of diversions above points of gaging. To these might be added the winter runoff as evidence of the effect of high winter temperatures.

(1) Soil priming can be a moderate factor where the autumn rain is normally heavy and does not drain greatly before snowfall. The lack of such moisture is particularly effective in using an undue proportion of the snow cover in priming the flow of its melt water. The period should cover the months of August to October, for winter accumulation of snow may begin by November.

(2) The water table akin to soil moisture is an impressive factor where flat land and meadow land are predominant above points of gaging, as particularly in the Humboldt Basin, Nevada, and the "Parks" of the eastern Continental Divide in Colorado. It seems far less dominant in the Sierra Nevada and western Continental Divide.

No factor for water table has yet been attempted in the present study, but will be included in the atlas of flow harmonics of the Colorado Basin being planned. Although the rise of the water table can be better traced by measurements in wells, heavy and continuous summer precipitation, and sometimes the preceding season's excessive flow of the streams, may afford semi-reliable assurance.

(3) Abnormal winter melting of the snow cover at the lower altitude zones may distort the forecast if not detected by low-altitude snow surveys and adjusted through the use of weights for the various altitude zones. Temperature departures alone will be insufficient, for the snow cover may be sufficiently deep or possess sufficient capillarity to sustain the melt without loss. Only the snow survey will provide definite data. The areas of the necessary zones can be readily computed and the temperature departure at central stations throughout the winter determined.

(4) Diversion effects above points of gaging can produce serious distortion but can be computed if the percentage of the snow cover is reliable. For where water is not rationed according to the percentage of the supply, the residual runoff at the foot of the stream or at the point of

gaging will vary according to the amount of diversion and the excess or deficiency of the supply. When the supply is normal, the diversions may be assumed to be normal, and the runoff at the gaging station will be normal.

In the seasons of 1939 and 1940, the snow cover indicated a water supply of only 83.5 and 71.0 per cent of normal, respectively, but the precipitation indicated a supply of 104.0 and 90.9 per cent, or approximately normal. No correction, therefore, would have been attempted in the precipitation data. However, an adjustment could have been made in the snow-survey data to a forecast of 76.0 and 56.5 per cent, respectively, or within + 12.1 and + 5.1 per cent of normal of the actual seasonal runoff.

The basis and computation are simple. The irrigated area of the upper Colorado Basin above Lee's Ferry is 1,464,000 acres (including Green, 637,000, San Juan, 181,000, and Dolores 52,000 acres). The water use may be set approximately at three feet, or a total of 4,500,000 acre-feet. Since the normal flow of the Upper Colorado at Bright Angel Creek is 9,006,000 acre-feet, the normal original supply furnished to the stream may be set at 13,500,000 acre-feet; that is, the residual flow plus the diversions. Thus we obtain the equation and variations shown in Table 13.

Table 13--Distribution of water supply for various percentages of normal flow, Upper Colorado Basin

Supply		Diversion for irrigation	Residue	
pct	ac-ft	ac-ft	ac-ft	pct
100	13,500,000	4,500,000	9,000,000	100
91 (1940 precip.)	12,285,000	4,500,000	7,785,000	86.5
84 (1939)	11,340,000	4,500,000	6,840,000	76
71 (1940)	9,585,000	4,500,000	5,085,000	56.5

The total irrigated area for the Upper and Lower Colorado is 2,638,000 acres and for the Upper and Lower Humboldt, Nevada, 286,000 acres. If the upper sections of these streams for which data are available are compared, the diversion factor of the Colorado is relatively small. For example, the Upper Colorado, with an irrigated area of 1,464,000 acres, has a residual flow of 9,006,000 acre-feet, while the Upper Humboldt, with an irrigated area of 170,000 acres, has but 215,000 acre-feet of residual flow. The acreage of the Humboldt is 11.3 per cent of that of the Colorado, but its residual water is only 2.4 per cent of the larger stream, a fivefold advantage to the Colorado.

It has been assumed that rationing is not practiced on the larger streams where water is abundant. On the Humboldt, where flood irrigation has become traditional, the water users were drowned out the past season by excessive flow built up by a high water table and summer precipitation twice normal.

Increase in accuracy of re-forecast on May 1; factor of precipitation during runoff, Colorado Basin--In addition to the factors that can be recognized on April 1 there is also the factor of precipitation during runoff that can be recognized only as it occurs. Fortunately the normal precipitation for April is 29 per cent of the total for April to July, and the precipitation for April to June, while the snow still covers considerable area, is 55 per cent of the period of runoff. The monthly percentage based on joint weighted mean for Green River, Grand Junction, and Durango is 29.1 for April, 25.8 for May, 15.5 for June, and 29.4 for July.

The precipitation for April to May is most effective and for April especially so, for practically the entire fall is caught by the snow cover which also provides the soil priming. Although the precipitation in July is highest of all four months, its efficiency in producing runoff is probably least, owing to the large proportion of bare ground at the close of the melting season.

Residual snow cover, Colorado Basin--The snow survey of May 1 is planned to afford a view of the snow cover still remaining from the cover of April 1. It represents a combination of the melting that has occurred plus precipitation during the period. The net loss of three inches (14.9 inches on April 1 minus 12.0 inches on May 1 (see Table 12) may represent a total loss by melting of five inches and an accretion of two inches of precipitation. Although the weighted mean precipitation shown by the average of the group of precipitation stations, most of which are at lower altitudes, is 1.3 inches, the weighted mean for three representative high-level stations is 1.93 inches. The weighted precipitation in April for the low-level stations (Green River, Wyoming 6083 feet, Grand Junction 4688 feet, Durango 6552 feet) was 1.1 inches. For the high-level stations (Kemerer, Wyoming 6954 feet, Fraser 8568 feet, Cascade 8853 feet) it was 1.93 inches.

The high-level stations represent more nearly the precipitation occurring on the snow cover and at the snow-survey stations. The precipitation of 1.93 inches or approximately two inches should be compared with the snow cover of 14.9 inches April 1 in seeking a correction factor for divergence from normal of the precipitation during runoff.

Correction factor for April precipitation, Colorado Basin--On the basis of the high-level precipitation in April of 1.93 inches to the snow cover of 14.9 inches on April 1, the precipitation during April represents a factor of 13 per cent in the runoff during April to July. But comparing the precipitation during April of 1.3 inches to that during October to March of 6.46 inches (both representative mainly of low-level conditions), the precipitation during April represents a factor of 20.1 per cent.

Or to compute the factor from the relationship of April to July to October to March, the precipitation during April is 29.1 per cent of that of April to July, which in turn is 55.9 per cent of that of October to March, or 16.3 per cent of the accumulation or pre-runoff period. In this estimate the winter precipitation is again 6.46 inches, but owing to lack of normals, the normal for April to July at Green River, Grand Junction, and Durango of 3.61 inches is used. Since, however, the precipitation in April, falling largely on the snow cover, is relatively much more effective than the precipitation of the other months of runoff, the factor should be increased to 20 per cent or even higher. In the Sierra Nevada where the factor is much less potent, LANDSBERG has estimated the correction factor for April to May combined at one-fifth or 20 per cent. The factor of 20 per cent for April alone for the Continental Divide does not seem too high. Further analysis of the precipitation during May, June, and July for the ten-year period with reference to variation between the adjusted forecast of May 1 and final runoff of April to July may lead to additional refinement.

This forecast factor, in case it increases or reduces the runoff supply markedly from the estimate for April 1, may require a further correction for the effect of diversions. Until the water is apportioned closely to the supply, lack of precipitation and attendant drying of the soil may complicate the forecast problem further. As already mentioned, excess precipitation and lack of need for even the usual allotment of water may create excessive water downstream. CLYDE E. HOUSTON sees here the close dependence of forecaster and water user.

The temperature factor during runoff, Colorado Basin--It is recognized that intensity of rainfall increases net runoff, and it is believed that accelerated melting of snow cover, as by Chinook, likewise increases the relative runoff. Conversely that slow melting, as during periods of subnormal temperature, diminishes the seasonal runoff below expectation.

But comparison of records within departure of approximately 10°F (average monthly) from normal has so far failed to reveal any consistent effect of temperature departure on the increase or decrease of the forecasted runoff. Table 14 presents details for seasonal comparison.

The seasons mainly above normal in temperature are 1936, 1939, 1940, and 1943. In each of these seasons the snow cover is greater than runoff. On the other hand, in 1944, which is mainly below normal in temperature, the snow cover is less than the runoff, but in 1945, though similarly deficient in temperature, the snow cover is about equally greater.

Thus there appears to be no consistency between high temperature and high water within the error of instrumentation. The phase of flow, however, is accelerated, or in case of low temperature is retarded. The total flow remains unchanged. The question of floods caused by rains and protracted high temperature deserves detailed study for it may lead to a definite factor clearly visible at high rates of melting.

Corrected forecasts, Colorado Basin--Table 15 indicates the corrections possible in the forecasts of April 1 and re-forecasts of May 1. The correction factors available are diversion April 1 and precipitation May 1. In a fully developed forecast, the other factors mentioned should if possible be included.

Accuracy, Colorado Basin forecasts--The accuracy of forecast on May 1 in the case of the snow cover is within 15 per cent for the ten years of record and for four years is within ten per cent. If wholly uncorrected April 1, the maximum variation between snow cover and runoff for

Table 14--Temperature departure from normal in degrees Fahrenheit during snow-melting period in the Colorado Basin, and divergence in per cent of normal of snow cover from runoff

Item		Month	Year									
Tributary basin	Station		1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
Green	Green River, Wyo.	Apr.	+ 1.6	- 2.2	+ 1.7	+ 4.9	+ 1.6	+ 0.8	+ 2.8	+ 7.6	- 1.0	- 4.0
		May	+ 6.3	+ 4.1	- 0.3	+ 4.0	+ 5.9	+ 3.2	- 1.4	- 1.3	+ 1.9	+ 2.2
		June	+ 5.6	+ 0.4	+ 3.8	- 2.2	+ 3.2	- 1.8	- 1.5	- 2.7	- 2.9	- 5.3
		July	+ 4.1	+ 3.2	- 1.1	+ 1.3	+ 1.7	- 0.7	+ 1.1	- 0.1	- 1.3	- 1.1
Upper Colorado	Grand Junction, Colo.	Apr.	+ 2.8	- 1.7	+ 0.8	+ 3.2	+ 2.0	- 3.2	+ 1.8	+ 7.9	- 4.4	- 4.5
		May	+ 4.8	+ 5.1	- 1.0	+ 4.7	+ 6.3	+ 2.4	- 0.7	- 0.2	+ 1.2	+ 2.5
		June	+ 4.4	- 0.4	+ 1.8	+ 0.8	+ 5.2	- 2.2	+ 0.6	- 0.7	- 2.0	- 4.8
		July	+ 2.2	+ 0.9	0.0	+ 2.4	+ 3.1	- 0.3	+ 1.7	+ 2.2	- 0.2	+ 0.9
San Juan	Durango, Colo.	Apr.	- 0.9	- 1.8	- 1.1	+ 2.5	- 0.3	- 3.7	+ 0.9	+ 4.3	- 4.9	- 4.4
		May	+ 0.8	+ 2.1	- 3.0	+ 0.8	+ 1.4	+ 1.2	- 2.8	- 1.6	- 1.1	- 1.7
		June	+ 1.8	- 1.7	- 0.5	- 1.0	+ 2.0	- 3.4	- 2.8	- 2.3	- 4.1	- 5.3
		July	- 1.7	- 0.8	- 3.0	- 1.3	+ 1.2	- 1.2	- 1.0	- 0.3	- 2.2	- 0.1
Divergence of snow cover from runoff, pct			+ 10.8	- 2.4	- 11.6	+ 3.1	+ 10.1	- 9.9	- 14.4	+ 10.4	- 11.8	+ 9.8

Table 15--Forecasts of runoff during April to July, Colorado Basin above Grand Canyon, corrected for diversion April 1 and precipitation May 1, in percentage of normal

	Year									
	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
Precipitation, October-March	73.0	105.2	118.5	104.0	90.9	133.8	132.2	110.9	92.0	96.7
Corrected for diversions, April 1[a]	....	....	....	....	86.8	....	....	....	....	....
Corrected for precipitation, May 1[b]	61.0	91.2	....	95.8	91.8	157.8	147.2	100.9	99.0	94.7
Revised forecast, May 1	61.0	91.2	118.5	95.8	91.8	157.8	147.2	100.9	99.0	94.7
Snow cover on April 1	118.8	109.4	113.4	83.5	71.0	99.8	98.4	106.1	95.6	102.0
Corrected for diversions, April 1	....	....	....	76.0	56.5	....	....	....	....	....
Corrected for precipitation, May 1,	106.8	95.4	113.4	67.0	61.5	123.8	113.4	96.0	102.6	100.0
Revised forecast, May 1	106.8	95.4	113.4	67.0	61.5	123.8	113.4	96.0	102.6	100.0
Runoff at Bright Angel Creek, April-July	96.0	97.8	125.0	63.9	51.4	133.7	127.8	85.6	114.4	90.2
Divergence in revised forecasts, precipitation compared to snow cover	- 45.8	- 4.2	+ 5.1	+ 20.5	+ 19.9	+ 34.0	+ 33.8	+ 4.8	- 3.6	- 5.3
Precipitation compared to runoff	- 35.0	- 6.6	- 6.5	+ 31.1	+ 40.4	+ 24.1	+ 19.4	+ 15.3	- 15.4	+ 4.5
Snow cover compared to runoff	+ 10.8	- 2.4	- 11.6	+ 3.1	+ 10.1	- 9.9	- 14.4	+ 10.4	- 11.8	+ 9.8

[a] For method of computing diversion effects, see p. 435.

[b] See p. 436, departure 100 per cent in April precipitation, departure 20 per cent in April-July runoff. Example: In 1936, 60 per cent of normal required a correction of 12 per cent.

five years is within 20 per cent and for the other five years is as great as 35 per cent. For the precipitation, three forecasts for May 1 out of ten were within ten per cent, but the other seven varied from 15 to 40 per cent.

Both the precipitation stations and the snow-survey courses should be arranged by altitude zones and more high-level precipitation stations provided. Yet the snow surveys will provide a more reliable index of winter melting than departure from normal temperature recorded at a central station.

Parallel normals will assure more accurate comparisons. The normals of snow cover and runoff are both based on ten years' record. The divergence between these and precipitation may be due in part to this cause. The large divergence in 1941 and 1942 when the snow cover was approximately 35 per cent of normal below the precipitation does not seem certainly to be due to winter melting if judged on the basis of temperature departure alone. The record at Grand Junction (Table 16) will illustrate.

Table 16--Temperature departure at Grand Junction in degrees Fahrenheit

Season	Month					
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1940-41	+ 3.2	- 1.3	+ 3.5	+ 8.0	+ 5.6	+ 0.6
1941-42	- 0.2	+ 1.7	+ 7.4	+ 4.4	- 4.3	- 4.4

Low-level snow surveys and the measurement of the stream flow will be more conclusive.

Other basins--The extension of the long-period analysis to the South Yuba and Colorado Basins should be applied also to the Columbia. Fortunately, the snow-survey data for most of the western watersheds have now been summarized and span a minimum period of ten years. The Tuolumne and American River Basins have been analyzed, and the Huntington Lake Basin will be compared with the Kaweah. California is planning a research project to improve forecasting.

The United States Weather Bureau probability water-supply forecasts

The new forecast system by the United States Weather Bureau based on precipitation and temperature has extended and statistically developed the minimum possible, probable, and maximum possible flow long used in forecasts to five divisions based on odds of 1 to 1 to 3 to 1, and 30 to 1 for long-range planners, particularly of hydroelectric power. The general method of the new forecast is presented in the "Seasonal water-supply forecasts for the Columbia River System," now in its third year and "Seasonal water-supply forecasts for the Great Salt Lake Basin" begun during the present season. These forecasts are issued the first of each month, beginning with January and continue during the period of major runoff. The United States Weather Bureau expects to prepare a paper on its procedure at some future date.

Special forecast problems: Mining

The problem of high water is as important as that of normal or low water but occurs less frequently. It is precautionary as is that of floods. The immediate problem is located in Canada and was proposed by GEORGE A. DAWSON, Steep Rock Iron Mines, Ltd., Steep Rock Lake, Ontario. The problem and suggested solution are indicated by the following extracts of correspondence:

JAY A. CARPENTER (Director, Mackay School of Mines, University of Nevada, Reno, Nevada, February 2, 1945)--GEORGE A DAWSON, a graduate of Mackay School of Mines, has asked "for information regarding procedures and methods of calculations of quantities of runoff water of snowfall as developed by Dr. CHURCH from his work in the Sierra Nevada Mountains." Engineer DAWSON is connected with a company that is pumping out a tremendous volume of water and silt from a lake in order to mine the iron ore on the lake bottom. Sufficient progress was made to start mining ore this past fall, but a large inflow of silt stopped production. The inlet stream to the lake was diverted, but the absorbing question now is the runoff to be expected from the melting snow.

J. E. CHURCH wrote DAWSON on the subject (March 26, 1945) as follows: Director CARPENTER of the Mackay School of Mines has indicated your interest in snow because of the effect of snow-melt runoff in re-flooding of Steep Rock Lake. The problem appears much like that of forecasting for the farmers in Tule Lake Basin as to whether they will be granted another period of scant water or must look forward to being drowned out.

For many years there were snow surveys in the St. Maurice River Basin near Montreal to determine the seasonal water supply, but these snow surveys may probably be no longer continued and the location is probably too remote from Steep Rock Lake for direct comparisons. Snow surveys in that watershed to determine the maximum inflow quantitatively into the lake bottom would be helpful. This method is called quantitative rather than percentage or proportional and has been carried on for many years in western Newfoundland; in the Androscoggin River Basin of Maine and New Hampshire the quantitative method has long been used with results sufficiently close to forecast the high water both for power and floating logs to market. Here in the West the general uniformity of the snow cover and vastness of areas have made the comparison between the annual snow cover and the average of many years the best means of determining the percentage of streamflow or lake rise in the area.

Information on details may be found in papers by various snow surveyors, members of the Committee on Snow, and snow-survey organizations. For quantitative measurements, it may not be necessary to take a great number providing only that the measurements are fairly well distributed so as to give a fair average of the water in the snow. In case only measurements of lake rise are available during past years and a precipitation station is nearby, the percentage of normal precipitation for the present winter and the probable corresponding rise in the lake from minimum to maximum can probably be determined.

I imagine, however, that you have a network of lakes in a glaciated basin sufficiently connected so that water may flow slowly from one to another. Further, that you have a tight bottom in your basin and except for the tundra will lose all of the snow melt in runoff or slow evaporation. But even the tundra will scarcely be sponge enough to save your lake from filling at least slowly.

Snow transport: Desired ideals

The absence of the vigorous younger men in the war has forced dependence for snow surveys onto the previous generation, whose knowledge of technique and determination are undiminished but whose physical reserve is lower. This change has quickly brought the need of snow motor vehicles to its inevitable climax. In his search for a motor and test particularly of the Tucker Sno-Cat, R. A. WORK, Research Project Supervisor of the Division of Irrigation, United States Soil Conservation Service, has set up the following 12 points as essentials: (1) Ability to travel on soft or sticky snow; (2) ability to ascend steep grades; (3) ability to traverse side slopes; (4) ability quickly to surmount obstacles such as fallen trees, rocks, and steep banked channels; (5) ability to ford flowing streams; (6) ability to operate on snow-bare ground; (7) mechanical dependability; (8) portability; (9) maneuverability; (10) safety; (11) speed; and (12) economy of operation. In all these respects, WORK [1946] finds that the Tucker sled shows maximum promise of usefulness.

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DISCUSSION OF

"FORECASTING STREAM-FLOW OF THE SALT RIVER, ARIZONA"

By C. K. COOPERRIDER, H. O. CASSIDY, and C. H. NIEDERHOF

[Trans., v. 26, pp. 275-282, 1945]

MATTHEW I. RORABAUGH (U. S. Geological Survey, Louisville, Kentucky, August 27, 1945)-- In regions where snow is not a factor there is some advantage in making forecasts based on the effects of travel time and base flow. However, the runoff which results from precipitation during the period of forecast usually constitutes a substantial portion of the flow in many streams, and accordingly these predictions may be highly speculative.

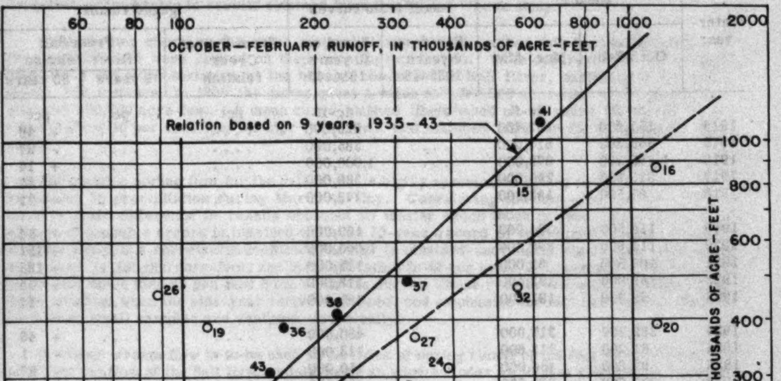

Fig. 1--Correlation between runoff, October to February and March to May.

The authors state that on March 1 an average of 52 per cent of the winter flow of Parker Creek has passed the gaging station on that creek while only 36 per cent of the winter flow of the Salt River has reached Roosevelt Reservoir. The forecast is based on this lag, which would approximate 16 per cent of the winter flow of the Salt River or about 25 per cent of the flow during March to May. In giving reasons for the lag the authors minimize the effect of accumulated snow, because less than 15 per cent of the Salt River Basin is thought to have accumulated snow. It may be, however, that the snow on this portion of the basin is the principal reason for the lag. The snow cover accumulates at high altitudes, where precipitation is heaviest and temperatures lowest. As losses will be proportionally less in these low-temperature areas than in the remainder of the basin, it follows that storage of 25 per cent of the flow could result from snow accumulation on less than 15 per cent of the basin.

If the lag is caused by snow accumulation, then it would be expected that correlation could be obtained between winter flow and spring flow of the Salt River near Roosevelt. Winter flow of Salt

Table 1--Data for Salt River near Roosevelt, Arizona

Water-year	Runoff[a]		Expected Mar.-May runoff from curves		Error of gaged runoff		
	Oct.-Feb.	Mar.-May	Based on 9 years; 1935-43	Based on 30 years; 1914-43	From Parker Creek relation	From Salt River relation	
						9 years	30 years
	ac-ft	ac-ft	ac-ft	ac-ft	pct	pct	pct
1914	153,800	152,400	....	225,000	....	....	+ 48
1915	555,300	814,000	....	585,000	....	....	- 27
1916	1,145,100	878,000	....	1,000,000	....	....	+ 14
1917	313,300	290,600	....	388,000	....	....	+ 33
1918	85,500	188,300	....	148,000	....	....	- 21
1919	114,500	394,900	....	180,000	....	....	- 54
1920	1,117,800	397,000	....	1,000,000	....	....	+ 151
1921	107,500	61,000	....	175,000	....	....	+ 186
1922	148,000	192,500	....	218,000	....	....	+ 14
1923	98,900	191,200	....	165,000	....	....	- 14
1924	389,200	315,000	....	460,000	....	....	+ 46
1925	61,200	113,600	....	113,000	....	....	- 1
1926	87,800	456,900	....	150,000	....	....	- 67
1927	327,800	370,200	....	400,000	....	....	+ 8
1928	91,400	120,700	....	153,000	....	....	+ 28
1929	78,800	169,500	....	139,000	....	....	- 18
1930	105,400	242,700	....	170,000	....	....	- 30
1931	194,660	188,100	....	272,000	....	....	+ 45
1932	558,400	475,700	....	600,000	....	....	+ 26
1933	186,100	160,600	....	260,000	....	....	+ 61
1934	90,380	56,430	....	152,000	....	....	+ 170
1935	216,270	413,270	385,000	291,000	+ 10	- 7	- 30
1936	167,100	382,500	300,000	240,000	- 18	- 22	- 37
1937	313,100	492,600	540,000	388,000	+ 16	+ 10	- 21
1938	64,160	204,010	123,000	126,000	- 38	- 40	- 38
1939	148,140	228,320	270,000	220,000	- 7	+ 18	- 3
1940	85,060	138,050	163,000	148,000	+ 65	+ 18	+ 7
1941	625,390	1,108,100	1,010,000	650,000	- 4	- 9	- 42
1942	210,380	272,870	375,000	285,000	+ 13	+ 33	+ 5
1943	155,860	306,890	282,000	225,000	- 13	- 8	- 27
				Mean	20	18	42

[a] From reports of U. S. Geological Survey.

River would be an integrated sample of the storms over the area in so far as they would produce low-altitude runoff and if used as an index could be expected to give as good or perhaps better results than using the smaller sample at Parker Creek.

A plot of runoff during October to February for Parker Creek against that for October to February for Salt River suggests the inadequacy of the runoff of Parker Creek as an index. The years of 1938 and 1940, which show wide deviations on the Parker Creek study, also show similar deviations on the relation curve during October to February. It appears that in those years conditions over the Parker Creek drainage were not representative of conditions over the Salt River drainage.

Using the same years as were used for the Parker Creek correlation (1935-43), the runoff of the Salt River for October to February (see Table 1) was plotted (solid points on Figure 1) against the runoff of the Salt River for March to May (see Table 1) and a mean curve (solid line) was drawn. The deviations of points from this curve show less scatter than those on the curve for Parker Creek, particularly in low years (1938, 1940). The mean error of predictions is 18 per cent by this study as compared to 20 per cent in the Parker Creek study. The correlation coefficient using Salt River as an index is 0.97, and the standard error of estimate is 75,000 acre-feet--comparable to results obtained from the Parker Creek study.

As a further check on the value of predictions by this method data for the Salt River for the years 1914-34 were plotted on the curve (open circles). It is apparent that the curve for 1935-43 is not representative of the normal condition for Salt River, particularly for high flows. For instance, in 1920 the curve gives a value of 1,750,000 acre-feet while gaged flow was only 400,000 acre-feet. A mean curve (dashed line), based on 30 years (1914-43), gives results about 40 per cent less at high flows than that obtained from the curve based on nine years.

Forecasting spring flow for the Salt River is highly speculative by any method because of the variations in precipitation during March to May. Considering the nine-year period (1934-43) there is little difference in results obtained no matter which index is used. However, a better picture of probable errors is obtained when the 30-year record of Salt River is used. For the 30-year analysis a correlation coefficient of 0.67 is obtained--not highly significant. The standard error is 180,000 acre-feet, and mean deviation is 42 per cent. It is noted that six of the 30 years plot more than 50 per cent from the mean curve. These results are quite different from those obtained when the nine-year record was used, and emphasize the fact that caution must be used when small samples are analysed statistically.

If winter stream flow is to be used as an index of spring runoff of the Salt River it would appear that the flow of the Salt River would make as good an index as Parker Creek flow (based on comparison of results of nine-year record). Since 30 years of record are available for the Salt River compared to nine for Parker Creek, thereby making a better determination of probable errors possible, and since the Salt River index is a basin sample where a local change in characteristics is apt to be offset by an opposite change elsewhere, whereas the Parker Creek index is a spot sample subject to local changes as by grazing, why not use Salt River winter flow as an index?

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DISCUSSION OF

"ARTIFICIAL DRAINAGE OF LAND: STREAMLINE EXPERIMENTS--THE ARTESIAN BASIN - III" by DON KIRKHAM

[Trans., v. 26, pp. 393-406, 1945]

E. C. CHILDS (School of Agriculture, University of Cambridge, Cambridge, England; received April 1, 1946)--Attempts to solve land-drainage problems by impeccable mathematical analysis are rare enough, and **KIRKHAM'S** latent contribution in this field is very welcome. The purpose of my present remarks is to discuss his weighing up of the relative merits of such analysis and the electrical analogue method which I have myself used. It is agreed that a complete mathematical analysis capable of giving detailed results comparable with those derived by analogues is still awaited; and I agree that such an analysis would be preferable if it were available, but my grounds are not the practical ones of KIRKHAM, who regards it as a relative disadvantage, presumably because of the labor and time required, that by my method a new analogue must be constructed for each particular new drain geometry.

One must of course face the fact that a complete solution, even limited to the steady state, is not impending. Those solutions involving a free surface (water table and surface of seepage) so far obtained have dealt only with open ditches [HOPF and TREFFTZ, 1921; VEDERNIKOV, 1936] or seepage through dams [DAVISON, 1936; HAMEL, 1934; MUSKAT, 1935], and not piped drains, and have ignored the capillary fringe. In every such case the free surface is also a streamline, a condition rare in drainage problems, whilst success in the dam problem hangs upon the fortunate accident that the hodograph of the system is the contour along which a known function (the modular function) is real; this happy accident is not repeated in the drainage problem [CHILDS, 1945]. It is to be hoped that this avenue will not be abandoned without being further explored by someone of stronger mathematical attainments than my own. In particular, VEDERNIKOV'S problem, so far as one can judge from a highly compressed communication, would seem to be applicable to the artesian basin, and may possibly prove to be capable of modification to deal with a system of drains instead of a single drain in an infinite basin.

Even if a solution is eventually obtained, it is quite likely to follow precedent in presenting a very formidable and time-consuming task in the calculation of particular numerical results from the general formal solution; it is open to anybody to demonstrate to himself that the time and labor required to produce, say, a numerical solution to a dam problem, following HAMEL or MUSKAT, is just as great as to construct an electric analogue. MUSKAT, in fact, calculates only one water table in his paper, in other cases freely drawing this surface between calculated terminal points by reference to the one calculated case. Further he suggests that the internal potential field and stream lines are most conveniently obtained by the electric analogue method after the boundaries have been calculated, rather than to undertake the great labor of numerical computation throughout.

The advantage of the mathematical approach seems to me to be twofold. Firstly it makes no appeal to experimental techniques and involves no demands upon personal skill, but even here it must be admitted that accurate enough results for this type of work are not difficult to secure by the analogue method, which, it may be added, is now being successfully developed to deal with non-steady states by equating current distribution at the "water table" with distribution of rate of fall of water table. Secondly there is the psychological factor, the satisfaction to be derived from producing an elegant formal structure into which can be fitted all observed facts. In his search for such a structure I wish KIRKHAM success.

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NOTES AND PERSONALIA

NOTES

Corrigendum--The following correction is noted in the Transactions:

Vol. 27, no. 2, April 1945, p. 299, last entry, Andrew R. Whitson was inadvertently reported as having died November 20, 1946. This should read, November 20, 1945.

New course in Geophysics at Columbia University--Columbia University announces the initiation of a course in General Geophysics to be taught by Maurice Ewing.

Glacial map of North America--A glacial map, 79 inches by 52 inches, has been published by the Geological Society of America, showing Pleistocene glaciation from the Aleutians and Iceland southward. Topographical features are shown by form line both on land and on the ocean bottom.

Seismological papers presented at the meeting of Society of Exploration Geophysicists--The following papers of interest to seismologists were read at the Annual Meeting of the Society of Exploration Geophysicists at Chicago, Illinois, April 1, 1946. Abstracts are given on pages 78-82 of the program of the meeting: (1) Paul F. Hawley, Geophysical contributions to vibration measurements and micro-chemistry; Darwin S. Renner, Seismometer engineering; Frank Rieber, Uses of the vibrotron in geophysics; R. L. Congon, The design and testing of a versatile dynamic seismometer; L. W. Gardner, Vertical velocities from reflection shooting; C. Y. Fu, Studies of seismic waves: propagation of elastic waves in the neighborhood of a free boundary.

New Offices of the Seismological Society of America--At the annual meeting of the Seismological Society of America in Berkeley, California, on April 19-20, 1946, the following officers were elected: Beno Gutenberg, President; Perry Byerly, Secretary; J. B. Macelwane, First Vice-President; Eliot Blackwelder, Second Vice-President; and Frank Neumann, Third Vice-President.

International Scientific Radio Union and Institute of Radio Engineers--May 2-4, 1946, a joint meeting of the American Section of International Scientific Radio Union and the Institute of Radio Engineers was held in Washington, D. C. Among the papers were the following: Electromagnetic signals produced by lightning, by S. Kass, L. A. Pick, and A. C. Trakowski, Jr.; Radar echoes from the nearby atmosphere, by M. W. Baldwin, Jr.; Detection of rapidly moving ionospheric clouds, by H. W. Wells, J. M. Watts, and D. E. George; Nomographic methods for the correlation, analysis, and prediction of ionospheric characteristics, by Marcella L. Phillips; the variability of sky-wave field intensities at medium and high frequencies, by N. Smith and M. B. Harrington; Correlation of magnetic disturbances with solar corona, by A. H. Shapley and W. O. Roberts.

Earthquakes in March and April 1946--On March 15 and on several days following, a series of strong earthquakes occurred in Southern California. The strongest shock, on March 15 about $13^{h}49.6^{m}$ U. T., was felt widely in Southern California and caused moderate damage. CHARLES F. RICHTER of the Seismological Laboratory, Pasadena, California, reported that falling boulders in Sand Canyon resulted in damage to the Los Angeles Aqueduct. He also stated that the earthquake was felt in Los Angeles and Pasadena with an intensity of III-IV (M-M scale of 1931). Los Angeles is about 100 miles south of the epicenter.

The following summary of information and comment on the earthquake and seismic sea-wave of April 1 was supplied by R. R. BODLE of the United States Coast and Geodetic Survey. The earthquake epicenter has been tentatively located at 54°N, 164°W, south of Unamak Island and off the extreme western end of the Alaskan Peninsula. The origin time was $12^{h}28.9^{m}$ U. T. Some revision of this determination may be required after more seismographic data are received. Press reports state the resulting sea-wave was noted at great distances from the epicenter; as far as the Cavancha Peninsula in Chile and Tahiti in the Society Islands east of Samoa. Adak Island, about 540 miles westward in the Aleutians, apparently escaped. (See note on seismic sea wave)

Three large waves were reported at Hawaii. These arrived at seven minute intervals shortly after 7 a. m. local time. The speed of such waves is greatly influenced by the depth of the water over which they pass. The rate increases with increasing depth and vice versa. The average speed of the waves that struck Hawaii approached 500 statute miles per hour. On April 8 the Red Cross listed the casualties as 119 dead and 80 missing. The need for warnings against such disasters has been widely discussed. In view of the rare occurrence of such phenomena it would be difficult to devise a workable system. The last destructive sea-wave reached Hawaii on April 2, 1868. Minor waves have occurred since that time but without damage. Warnings based on seismographic data involve considerable uncertainty as it is impossible to determine when a sea wave will result from a submarine earthquake. Warnings might be sent in the case of very large earthquakes, but there is the danger of sending too many warnings without attendant sea-waves. Some scientists in Hawaii have suggested the sending of direct radio messages from the Aleutian area when actual waves are observed there. Such warnings probably would prove quite satisfactory.

The following epicenters were reported by the United States Coast and Geodetic Survey and the Jesuit Seismological Association cooperating with Science Service and a selected group of widely scattered seismological stations.

Date	Time U. T.	Location and remarks
March 15	$13^{h}49.6^{m}$	35°.7 N, 118°.0 W USCGS Provisional
April 1	12 28.9	54°N, 164°W, USCGS Tentative
April 11	01 52.5	1°.5 S, 13°.5 W, JSA Tentative

Seismic sea wave of April 1, 1946--The following preliminary data on the seismic sea wave of April 1, 1946 which wrought such havoc in Hawaii were supplied by the United States Coast and Geodetic Survey, through E. C. McKay, Chairman of the Special AGU Committee for Cooperation with the International Commission for the Study of Tidal Waves. The epicenter of the earthquake causing the wave was located at latitude 53-1/2° north, longitude 163° west, south of Unimak Island, Alaska. The time of origin was $12^{h}28.9^{m}$ Universal (Greenwich Civil) Time.

Location			Time of arrival (U. T.)	Distance from epicenter	Travel time	Aver. Vel.	Initial rise of water	Initial fall of water	Period of initial oscillation	Max. range of oscillations	Time interval from arrival to max. oscillation
Place	North lat.[a]	West long.									
	° ′	° ′	h m	Stat. mi.	h m	mi/hr	ft	ft	min	ft	h m
Hawaii											
Honolulu	21 18.4	157 52.0	17 03	2241	4 34	490	0.7	2.2	12.5	4.1	0 30
Alaska											
Yakutat	59 32.8	139 44.1	b	974	...	...	...	...	b	2.4	...
Sitka	57 03.0	135 20.4	15 25	1108	2 56	378	...	...	b	2.6	9 25
Juneau	58 17.9	134 24.7	c	...	...	...	...	...	...	...	...
Skagway	59 26.5	135 19.5	c	...	...	...	...	...	...	...	...
Ketchikan	55 20.0	131 37.5	c	...	...	...	...	...	...	...	...
British Columbia											
Clayoquot	49 09	125 55	16 47	1610	4 18	374	0.7	1.0	9.0	1.9	4 10
Victoria	48 26	123 23	17 48	...	...	...	0.1	0.2	9.0	0.7	1 30
Washington											
Neah Bay	48 22.1	124 37.0	17 00	1687	4 31	373	0.3	0.4	10.0	1.2	2 40
Friday Harbor	48 32.8	123 00.4	18 40	...	...	...	...	...	b	0.2	...
Seattle	47 36.2	122 20.3	c	...	...	...	...	...	...	...	...
Bremerton	47 35.5	122 38.0	c	...	...	...	...	...	...	...	...
California											
Crescent City	41 44.7	124 11.8	17 07	1950	4 38	421	1.0	2.2	12.0	5.9	1 55
San Francisco	37 48.4	122 21.5	18 00	2197	5 31	398	0.5	1.1	15.0	1.7	2 25
San Francisco Bay	37 43.8	122 21.5	18 12	...	...	...	0.2	0.4	14.5	0.5	2 15
San Francisco Bay	37 46.5	122 17.9	18 23	...	...	...	0.3	0.9	13.0	1.4	2 20
San Francisco Bay	37 35.5	122 19.3	18 50	...	...	...	...	...	...	0.1	...
San Luis Obispo Bay	35 10.2	120 44.4	18 05	2392	5 36	427	1.3	3.3	18.0	8.5	1 25
Port Hueneme	34 08	119 12.3	18 23	2504	5 54	424	0.5	1.1	11.0	5.5	2 40
Los Angeles Harbor	33 45.0	118 14.6	b	2563	...	...	...	...	b	1.8	...
Los Angeles Harbor	33 43.2	118 16.3	b	...	...	...	...	...	b	2.5	...
Los Angeles Harbor	33 45.4	118 15.8	b	...	...	...	...	...	b	2.2	...
La Jolla	32 52.0	117 15.5	18 40	2646	6 11	428	0.5	1.1	10.5	1.4	0 45
San Diego Bay	32 42.8	117 10.4	19 15	...	...	...	0.2	0.3	10.5	1.2	2 40
Costa Rica											
Puntarenas	9 58.4	84 49.9	b	...	...	...	...	...	...	...	...
Columbia											
Buenaventura	3 54	77 05	b	...	...	...	...	...	...	...	...
Peru											
Talara	4 34.6[d]	81 17.3	27 00	6134	14 31	422	0.5	1.3	15.0	3.2+	e
Matarani	16 59.8[d]	72 07.3	28 55	7193	16 26	438	0.3	0.6	b	5.0+	e
Chile											
Antofagosta	23 39 [d]	70 25	29 50	7622	17 21	439	0.4	1.6	19.0	5.9	2 00
Valpariso	33 01.5[d]	71 38.4	30 36	8066	18 07	445	0.8	2.4	18.0	5.0+	e

[a] North latitude, except as indicated by [d].

[b] Indefinite because of local seiche.

[c] Effects of sea wave not noticeable on tide record.

[d] South latitude.

[e] Indefinite because of break in tide record.

Aurora of March 23, 1946--Douglas F. Manning, of Alexandria Bay, New York, has supplied the following description of the Aurora of March 23, 1946:

Beginning at twilight around 19^h10^m as an active rayed arch which was about half way from the horizon to the zenith from northwest to northeast, the color quickly changed from apple green to a crimson red. After about 15 minutes the red died away in the northeast and became most conspicuous in the northwest while in the north and northeast the green prevailed. This rayed arch which also took the form of streamers and patches soon formed a green glow all over the north and northeast with a very well-defined border. In the northeast a broad band of climson aurora, like a searchlight, reached up to the zenith where a partial corona formed with streamers coming up from all directions except from the south and southwest. The remarkable feature was the sharp contrast between the green light and the red crimson so close to each other. The crimson appeared much lower than the green. All this took place between 19^h15^m and 20^h00^m, after which the aurora died down considerably and almost disappeared with the exception of an occasional outburst of isolated rays of greenish hue which would soon die out. At 21^h30^m there remained only a green glow in the east and northeast. The forms seen were of the types illustrated in Störmer's Photographic Atlas of Auroral Forms on plates 10, 25, 26, 40, 41, 42, and 43 ending in form shown on Plate 31 in a partial corona which appeared to center just southeast of the zenith.

Japanese Committee for the Exploration of the Ocean--In 1942 the Japanese Society for the Promotion of Scientific Research appointed a committee designated as the Fourteenth Special Committee for the Exploration of the Ocean. Meetings were held monthly during the war. The membership is as follows: Dr. T. Okada, Chairman, Academy of Science (Oceanography); Dr. T. Akiyoshi, Hydrographic Department (Oceanography); Dr. M. Ishibashi, Kyoto Imperial University (Chemistry); Dr. M. Uda, Kobe Marine Observatory (Oceanography); Dr. K. Uwatoko, Tokyo Imperial University (Geology); Lt. Cdr. S. Otsuka, Hydrographic Department (Oceanography); Mr. I. Omura, Vice-President, Imperial Petroleum Company (Petrology)(deceased); Dr. S. Kokubo, Tohoku Imperial University (Biology); Dr. K. Kimura, Imperial Fisheries Experimental Laboratory (Physical Oceanography); Dr. K. Kimura, Tokyo Imperial University (Oceanography); Mr. S. Kuwahara, Hydrographic Department (Oceanography); Mr. F. Tada, Tokyo Imperial University (Geography); Dr. Y. Takenouti, General Central Meteorological Observatory (Hydrology); Dr. H. Tominaga, Tohoku Imperial University (Chemistry); Dr. M. Nakana, Hakodate Marine Observatory (Oceanography); Dr. H. Niino, Imperial Fisheries Institute (Physical Oceanography); Vice Admiral D. Soezima, Hydrographic Department (Physical Oceanography); Dr. T. Nomitsu, Kyoto Imperial University (Hydrography and Hydrology); Dr. T. Hayashi, Osaka Imperial University (Geochemistry); Dr. S. Hanzawa, Tohoku Imperial University (Geology); Dr. K. Hidaka, Tokyo Imperial University (Oceanography); Dr. S. Fujiwara, General Central Meteorological Observatory (Meteorology); Mr. Y. Matsudaira, Kobe Marine Observatory (Chemistry); Dr. Y. Miyake, General Central Meteorological Observatory (Oceanography); Mr. S. Miyahara, Hydrographic Department (Oceanography-Tides); Dr. S. Yoshimura, Primary Academy, Tokyo (Geography); Dr. T. Kozu, Academy of Science (Geology); and Dr. D. Nukiyama, Tokyo Imperial University (Meteorology).

Resumption of publication of "La Houille Blanche"--The French publication, La Houille Blanche (White Coal) has resumed publication as one devoted to the interests of hydraulic engineering. The first issue of the new series, which arrived in this country recently, has the approximate size of Civil Engineering. It includes a paper on the story of the Bissorte high head water power plant during the war, one on graphical solution of wave routing in open channels, and others on the influence of constrictions in rivers, and the destruction of the Möhne and Waldeche dams by the R. A. F. in Germany and other interesting material [see Bibliography, Hydrology, this issue]. It is suggested that persons and libraries interested in copies or subscriptions write to M. Pierre Danel, 10 rue de Belgrade, Grenoble, France.

New President at Colorado School of Mines--The Board of Trustees of the Colorado School of Mines has announced the appointment of Ben Hutchinson Parker as President of the School.

PERSONALIA

H. P. Berlage, Jr., formerly with the Royal Magnetical and Meteorological Observatory in Batavia, Java, has survived the Japanese occupation and is living in Bandoeng, Java.

Fred Betz, Jr. has accepted the position of Professor of Geology at Lehigh University and will assume his duties beginning with the Summer Session of 1946. He will continue to do part-time work for the Military Geology Unit of the U. S. Geological Survey with which he has served since October, 1943.

Wilmot H. Bradley, Chief Geologist with the U. S. Geological Survey, has recently been elected to the National Academy of Sciences.

Perry Byerly, Professor of Seismology at the University of California, has been elected to the National Academy of Sciences as a Geophysicist.

Sidney Chapman of Oxford University, Oxford, England, has been elected Foreign Associate of the National Academy of Sciences at its annual meeting April 22 to 24.

Andrew H. Clark, who has recently returned from China, has been appointed Associate Professor of Geography in the Department of Geology and Geography at Rutgers University.

John A. Fleming, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, was elected a member in the Norwegian Academy of Sciences and Letters on March 22, 1946. The election was in the Section of Mathematics and Natural Science.

Richard H. Fleming has recently taken up duties as Chief of the newly created Division of Oceanography in the U. S. Hydrographic Office. Since 1941, Dr. Fleming has been on leave from the Scripps Institution of Oceanography, and in the interim has served as Chief of the Oceanographic Section, and later as Assistant Director of Fundamental Research in the Division of War Research of the University of California.

John C. Geyer, until recently on military leave from the Department of Civil and Sanitary Engineering, Johns Hopkins University, as a Lieutenant in the Navy, has returned to this University as an Associate Professor.

Marion H. Gilmore, until recently on leave from the U. S. Coast and Geodetic Survey as Lieutenant Commander on microseismic research, has taken up his new position as Chief Geophysicist for the Navy project of detecting hurricanes and typhoons with the seismograph.

Gail A. Hathaway, Special Assistant to the Chief of Engineers, U. S. Army, has been designated a vice-president of the American Society of Civil Engineers.

M. Hotine, Brigadier, and Director of Military Surveys of the British War Office, has been appointed Director of the Colonial Geodetic and Topographical Surveys of the British Colonial Office. **G. I. Humphries**, until recently with the Nigerian Survey Service has been appointed Deputy Director.

Floyd W. Hough, who, as the commanding officer of the "Hough Team" of engineers in Germany, securing maps and other geodetic material, has been awarded the Legion of Merit, has been made Chief of the Geodetic Division of the Army Map Service. His chief civilian aide on the work in Germany, **David L. Mills**, has been awarded the Bronze Star, and is now his Assistant in the Army Map Service.

Ralph B. Kennard has returned to the United States from Biarritz American University and has returned to his duties as Professor of Physics at Wilson Teachers College in Washington, D. C., from which he has been on leave of absence since 1941.

Frederick Klein has been appointed a Lecturer in Engineering at the Institute of Geophysical Technology of St. Louis University. He was formerly Stress-Analyst of the McDonnell Aircraft Company, St. Louis, Mo.

Stuart Meyers, until recently Engineer with the U. S. Engineer Office in Rock Island, Illinois, has accepted a position in the Canal Zone.

Wendell Phillips Woodring, Principal Geologist with the U. S. Geological Survey, has recently been elected a member of the National Academy of Sciences.

C. S. Piggot, Physical Chemist with the Geophysical Laboratory, Carnegie Institution of Washington, on leave as Captain in the Navy, has recently been elected a member of the National Academy of Sciences.

K. L. Sherman, Physicist, Department of Terrestrial Magnetism of the Carnegie Institution of Washington, received the 1945 award of the Washington Academy of Sciences for outstanding achievement in Engineering Sciences, at the meeting of the Academy on March 21, 1946. The award was made on the basis of **Sherman's** work in connection with the development of instruments for measuring the elements of terrestrial magnetism and atmospheric electricity.

Phillip S. Smith retired on April 1, 1946 as Chief, Alaskan Branch, U. S. Geological Survey.

Herschel R. Snodgrass has accepted a professorship in physics at the University of California at Berkeley. Until recently he was Assistant Professor of Physics at the University of New Mexico.

Kenneth C. Spengler, until recently Lieutenant Colonel in the Army Air Forces Weather Service, has been appointed Executive Secretary of the American Meteorological Society, which has established new headquarters at 5 Joy Street, Boston 8, Mass.

H. U. Sverdrup, Director of the Scripps Institution of Oceanography, has been elected President of the International Association of Physical Oceanography to succeed B. Helland-Hansen, who has been elected President of the International Union of Geodesy and Geophysics.

Allyn C. Swinnerton, Professor of Geology at Antioch College, has been awarded the Legion of Merit by the War Department. Presentation of the medal was made at a ceremony at the College on April 18. The citation indicated that Lieutenant Colonel (then Major) Swinnerton "rendered outstanding service in a complex geological field" and that "his achievements materially aided the war effort and will be of lasting benefit to United States Military communications." Professor Swinnerton served in the Office of the Chief Signal Officer in Washington and later as Director of the Long Branch Signal Laboratory at Fort Monmouth, New Jersey. His principal work was in research and development relating to quartz crystals. He returned February 1 of this year to his former position at Antioch College.

Merle A. Tuve, Chief Physicist, Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been elected to the National Academy of Sciences.

T. Wayland Vaughan was named the recipient of the Mary Clark Thompson Medal by the National Academy of Sciences "in recognition of his outstanding achievement in such purposeful and ingeneous coordination of observations and generalizations made in and bearing on the fields of stratigraphic geology and paleontology."

F. A. Vening Meinesz, who came to the United States in November, 1945, to renew Dutch-American scientific relations and to arrange for exchange of students in the sciences, returned to The Netherlands in April. He traveled extensively during his stay here. At the University of Cincinnati he gave a series of four lectures under the sponsorship of the Cincinnati Chapter of Sigma Xi and the Departments of Geology and Physics on the subjects, "Gravity anomalies in the East and West Indies," "Tectonic patterns of the ocean flow and their interpretation," "Newer conceptions of isostory and crustal structure in the light of gravity determinations," and "Weighing the Earth from a submarine." He has left an interesting and valuable paper with the AGU on the subject "Tectonic shear-patterns of the Earth's crust" that will be published subsequently. Dr. Vening Meinesz expects to return to this country again in the late summer.

Robert A. Bartlett, noted explorer who was in the expedition of Robert E. Peary when Peary discovered the North Pole in 1909, died April 18, 1946 in New York City at the age of 70. He was a native of Newfoundland, and came from a seafaring family. His career as an explorer began in 1897 when he wintered at Cape D'Urville, Kane Basin, in company with Peary, and continued actively until 1935 when he went to northwestern Greenland under the auspices of the Field Museum and the Smithsonian Institution.

Charles H. Deetz, Cartographic Engineer with the U. S. Coast and Geodetic Survey for 47 years, died in Baltimore on January 27, 1946 at the age of 82. He is the author of "Cartography," and, in collaboration with Oscar S. Adams, of "Elements of Map Projection." During the War he returned from retirement to Federal service to bring these publications up to date.

Charles F. Devine, Cartographic Engineer in the Hydrographic Office of the Navy Department, died June 20, 1945. He was born in Philadelphia, and received his formal education at Pennsylvania State College. He spent the early years of his professional life in general engineering and construction, and worked with the Hydrographic Office from 1923 until his death. In the 1930s he was engaged on Navy geodetic surveys in Central and South America.

Jose A. Elliott, President of the Wyoming Development Company, Wheatland, Wyoming, died on August 25, 1945 after a lingering illness. He was born in Grundy County, Iowa on September 27, 1886 and studied at Cornell College (Iowa). Since 1909, he had been engaged on hydraulic irrigation and related work with the Wyoming Development Company.

Charles Fabry, until recently the President of the International Council of Scientific Unions, died December 11. 1945 in France at the age of 78.

Robert H. Smith of Jackson, Mississippi was killed in an automobile accident near Delhi, Louisiana on the evening of March 26, 1946 at the age of 30 years. At the time of his death, he was in the service of the Texas Company as a geologist. He was a graduate of Princeton University and obtained the degree of Master of Science from Louisiana State University in 1940. From that time until 1945 he worked with the U. S. Waterways Experiment Station at Vicksburg, Mississippi as a geologist.

Claude W. Sopp, for several years Assistant Chief Engineer and General Manager of the Water Department of Pasadena, California died on March 31, 1946 at the age of 51 years. He was a frequent contributor to literature relating to hydrology and hydraulic engineering. Prior to his work with the Pasadena Water Department he had worked with the Water Resources Branch of the U. S. Geological Survey.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

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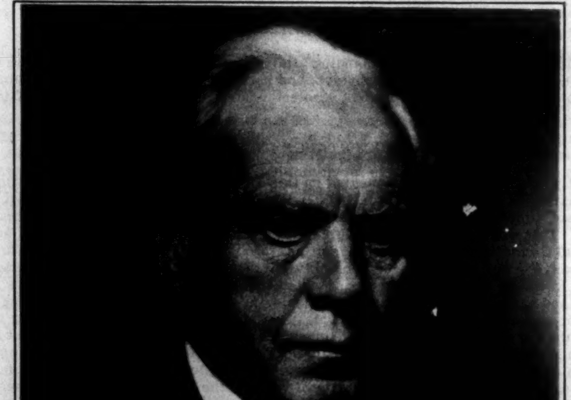
EIGHTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Chester R. Longwell

Mr. President: I am honored with a pleasant task in this brief ceremony. In seven successive years, the William Bowie Medal has been awarded by this Union, in recognition of distinguished attainment and outstanding contribution to the advancement of cooperative research in geophysics. The seven earlier awards have gone to scientists with broad interests; but each has fittingly represented one of the original sections of the Union. If a particular section is recognized in this year's award, it is, of course, the youngest of the eight, Tectonophysics. However, Volcanology might well claim this recipient--Oceanography also; the geodosists and seismologists know him as a co-worker with strong interests in their fields; and members of the other sections recognize him as a student of the Earth in all of its many aspects. In short, as a broad-gauged geologist, he is by the same token a broad-gauged geophysicist.



Professor Reginald Aldworth Daly
Recipient eighth award of William Bowie Medal
May 28, 1946
(Photo courtesy Fabian Bachrach)

It would be presumptuous for me to give to this audience a review in detail of the career and accomplishments of R. A. DALY. You know him and his works. It will suffice to remind you that he began his career, as every geologist should, with broad field study and mapping in difficult terrane. Throughout a busy life, he has exhibited two outstanding passions: to bring together as many geologic facts as possible, and to fashion from these facts clues to the geologic processes and to the complicated history of the Earth. He early mastered petrography, not merely from curiosity about the texture and composition of rocks, but as a means of deciphering the origins of rock masses. He delved especially into the complexities of igneous bodies, to learn the messages they have brought from the depths. In his long attention to geologic structure, one of his major interests, he has not been concerned with merely descriptive, geometric study; his viewpoint is emphatically that of dynamics, with the object of discovering the deforming forces and their ultimate origin. His incursions into broad geomorphic fields--involving coral reefs, strandlines, features of glaciated regions, submarine valleys--have had this same incentive of prying into the innermost secrets of Earth-dynamics. The wide horizons of his own mind are reflected in his oft-repeated admonition, "Think to scale."

The terms of the Bowie Medal emphasize "cooperative research in geophysics." Cooperation has always been a mainspring of DALY'S creed and practise. In his attack on any problem, he marshalls to the full the contributions of other workers. In return, he has broadcast freely, through a continuing flow of publications, the constructive and stimulating results of his own fertile thinking. He has encouraged and inspired specific research by individuals and by organizations. In particular, he has labored to direct the energies of research along geophysical lines, from a conviction that hope for solving the abstruse problems of the Earth lies only in pooling of efforts, by individuals and groups in all disciplines, with increasing appreciation of the quantitative viewpoint and method. Above all, his daring vision in pointing out new lines of attack has been a powerful catalyst, compelling progressive thought among his fellow geologists, and attracting the aid of workers and techniques in allied fields. This is scientific cooperation at its best.

Dr. ADAMS, because of his own outstanding attainments, particularly in the field of tectonophysics, but also in other aspects of geophysics, and because of his effective contribution to cooperation in geophysical research, I present with enthusiasm, as William Bowie Medallist for 1946, REGINALD ALDSWORTH DALY.

REPLY AND ACCEPTANCE BY PROFESSOR DALY

I am greatly honored and as truly puzzled by this 1946 award. And in the preparation of his gracious and flattering address Professor LONGWELL was puzzled. He knows I am not a geophysicist, but he had a job to do and thought to save his conscience by classing me as a "broad-gauged geophysicist." That was too generous a solution of his problem. With all due respect to him and the Bowie Medal Committee, may I class myself as "propagandist for geophysics." This phrase represents a fact, the only fact that could possibly warrant my inclusion among the holders of the Bowie Medal. Ever since Mount Ascutney presented its riddle to me, nearly fifty years ago, I have felt, and again and again stressed on paper, the geologist's need for quantitative thinking that is based on proper and well-controlled experiment. Then, too, I have sensed increasingly the need of correlation in the reverse: the duty of the geophysicist to see that any conclusion about the existing state of the Earth is consonant with the geologically determined changes of our planet since its birth some two billion years ago. This second conviction has long guided me in selecting for field investigation regions or rock bodies where data of value to the geophysicist might be secured. From each of these many fields I have brought problems, questions, hypotheses, all of them begging help from the geophysicist, armed with his tools of precision. Yes, as a tireless advocate of cooperation in earth science, the root principle of this American Geophysical Union, I can accept this beautiful medal with something like a straight face. On one side of it I read the names of eight sciences. Geology has as many specialties. Each of these sub-sciences is like a rocket, bursting out with new discoveries, new problems, and new techniques. Those of geophysics have the common goal of making ever truer and more vivid a picture of the Earth in its present state. The techniques have become elaborate and highly special. Yet seldom is an important discovery in one of the eight sciences established before it has been shown to obey principles of one or more of the sister sciences. Hence mind must meet mind, not only in the printed word but also in person. This philosophic necessity led to the founding of the American Geophysical Union, as unique as the Bowie Medal itself. One way to be a full-fledged member of the Union is to be a geologist, intent on bringing to the real geophysicists for experimental solution problems of the Earth's evolution, for the solution of these is one of the best guides to the properties of the Earth as it is. It seems that because I, a geologist, have asked in print many questions vital in geophysics, this signal reward of effort has been given me, and with it some assurance that attempts to synthesize the myriad facts of geology even in the form of bold speculations have not been intolerable for those who cultivate the vast field of controlled, experimental research.

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USE OF SHORAN IN GEODETIC CONTROL

Carl I. Aslakson and Donald A. Rice

Abstract--A general description of the shoran equipment is given, with a discussion of the various factors which influence accuracy of a direct distance measurement made by determination of the travel time of a radio signal. The line-crossing method of observation is explained, and problems arising in the computation and adjustment of a shoran triangulation scheme are briefly enumerated. A table summarizes results obtained in recent accuracy tests simulating field conditions to be encountered in the execution of geodetic control by shoran.

Principles

It is a well known principle of geodesy that geographic positions of comparatively nearby points may be in error by several seconds, relative to one another when the positions are independently determined by astronomic observations. The importance of this fact has been greatly emphasized in the course of military mapping operations of the past few years, and it has become desirable to investigate various means of increasing the maximum effective range of geodetic control operations beyond that available by the use of conventional methods.

Such a method has been developed during the past year by the 311th Reconnaissance Wing, United States Army Air Forces, through the adaptation of a precise air navigation system, shoran, to the problem of geodetic control. Shoran enables the direct measurement, by electronic means, of distances up to 500 or 600 mi with geodetic accuracy. The equipment was originally designed to establish the position of an airplane by distance measurement to two ground stations of known position, the airplane having a maximum altitude of 40,000 ft and the corresponding maximum measured distances being about 300 mi. In geodetic operations, a revised procedure is followed. Shoran readings are used to determine the minimum sum of the distances from the airplane to two ground stations, and a scheme of triangulation is built up from these sum distances in much the same manner that conventional schemes are formed from the measurement of horizontal angles. It is apparent that by this procedure the effective range of shoran is doubled, since each of the measured distances may approach the maximum range of the equipment.

To attain the greatest possible accuracy several refinements have been made in the original shoran operating methods. These refinements are fully described in a series of reports issued by the Seventh Geodetic Control Squadron of the 311th Reconnaissance Wing and will be treated briefly in this paper. During the course of the investigations, cooperation has been effected with the Division of Geodesy, United States Coast and Geodetic Survey, in the solution of certain problems, the most important of these being the derivation of a velocity correction formula and assistance in the development of new methods for the computation and least squares adjustment of triangulation schemes to be observed by shoran.

Basically, the shoran equipment consists of three main units, the airborne transmitter-receiver-indicator and the two ground station transponders. In operation, the airborne station transmits extremely short pulses at a rate of about 930 per sec, alternately on two different frequencies, the frequency change-over being effected by a vacuum relay at a rate of approximately ten per sec. These pulse groups are alternately received at the two ground stations and retransmitted (on a third frequency common to both) back to the airborne station, where they appear on a cathode ray indicator provided with a precisely controlled circular sweep which serves as the time base. A marker pulse is fed into the indicator directly from the pulse generator to serve as a reference for the transit-time measurement. Generation of the transmitted pulses is advanced by a series of goniometers or phase shifters until the returned pulses from both ground stations exactly coincide with the marker pulse on the screen. The amount of advance is then read from the goniometer dials in terms of distance to each of the ground stations. Lags in the various circuits and connecting cables are predetermined and inserted as corrections to the zero settings of the goniometer dials. The goniometers are calibrated in miles and read to a maximum accuracy of 1/1000 mi.

It is apparent that the accuracy of a geodetic distance as measured by shoran is dependent on three basic factors: (a) Accuracy of the measured time interval; (b) accurate knowledge of propagation velocity along the path; and (c) relationship between length of the propagation path and geodetic distance between the ends of the path. These factors will be considered in sequence.

Accuracy of the measured time interval--There are three basic elements in the accuracy of transit-time determination: (1) Time base frequency; (2) accuracy of the goniometers or phase shifters; and (3) inherent lags in the circuits and connecting cables. Errors in the time base frequency are negligible, the frequency being governed by a high-precision temperature-controlled oscillator. The goniometer errors have been found to be more serious in their effect on the final result. Theoretically, the phase advance produced by a goniometer is linear with respect to the angular rotation of the goniometer dial, but manufacturing tolerances are such that a deviation from linearity of several degrees may occur. To illustrate the effect of this error, it is pointed out that a deviation of 4° produces an error of about 50 ft in the dial reading. This error may be reduced by making the observations in such a manner that different goniometer settings are used in successive distance measurements, a procedure which may be compared to the established practice of using different circle settings in the measurement of horizontal angles with a theodolite. Errors introduced by uncertainties in lag of the various circuits and cables tend to be systematic in a given installation, and careful adjustment is required to minimize this effect.

Accuracy of propagation velocity--The shoran dials are calibrated to read correct path distance assuming the propagation velocity to remain constant at its sea-level value along the entire path. Since the path may extend to altitudes of 30,000 ft or more, it is evident that the decrease of air density and moisture content with altitude produces a significant effect on dielectric constant and consequently on propagation velocity. To illustrate, this change in dielectric constant results in a velocity correction of about 50 ft in the case of a plane altitude of 25,000 ft and a shoran distance of 200 mi. A formula has been developed for determination of the velocity correction as a function of plane altitude, ground station altitude, and shoran distance. The constants of this formula are dependent on the dielectric constant-altitude relation existing in the NACA Standard Atmosphere, modified to include a mean moisture lapse rate. Actual soundings taken in various regions of the United States indicate that this standard atmosphere may generally be used, although in certain cases the accuracy of the formula is increased by computing constants for several type atmospheres and using that type which most nearly approximates the soundings available at the time and place of observation.

The accuracy of propagation velocity along the path is, of course, directly related to the accuracy of the sea-level velocity used in calibrating the shoran timing unit. The basic physical value now used is the velocity of light in a vacuum, which after reduction to standard sea-level dry air conditions gives a calibration velocity of 186,218 mi/sec. The precision of this value is uncertain, but is probably about one part in 50,000. It is anticipated that recent developments in micro-wave technique will make possible the accurate determination of radio propagation velocity directly by phase comparison over a precisely measured base, and thus decrease uncertainty in the velocity constant.

Relation between path length and geodetic distance--The shoran path is assumed to be a circular curve extending from the ground station having an altitude K to the airborne station at altitude H, the path curvature being a result of the decrease of refractive index with respect to altitude. If the refractive index gradient were constant, the shoran ray path would be a circular curve with radius depending upon the amount of gradient. Actually the gradient follows a generally decreasing trend as the altitude is increased, resulting in an increase in path radius. Experience has shown that a mean path radius may be adopted for the geometrical correction formula. Having determined this radius value, the reduction to sea-level geodetic distance M is accomplished by a series of four corrective terms as shown below.

$$\begin{aligned} M = S &- (2.3920 \times 10^{-8})[S(H + K)] - (1.7935 \times 10^{-8})[(H - K)^2/S] \\ &+ (0.24848 \times 10^{-8})S^3 - (1.6083 \times 10^{-16})[(H - K)^4/S^3] \quad \ldots\ldots\ldots\ldots\ldots (1) \end{aligned}$$

where H and K are in ft and M and S are in mi. It is interesting to note that the terms of formula (1) bear a significant resemblance to certain of the corrections commonly used in geodetic surveying. The first term suggests the correction used in reducing a measured base to its sea-level value; the second and fourth are analogous to those used in correcting a catenary for slope; and the third term provides the rectification from path curvature to earth curvature. The coefficient of the third term contains the earth radius and path radius, both assumed to be constant. The fourth term is rarely required, being negligible unless the slope of the path exceeds one part in ten.

In this derivation of the geometrical formula, certain assumptions have been made for the purpose of simplification. Errors resulting from these assumptions have been evaluated, and tables and curves prepared to facilitate modification of the formula when required. Considering the observational accuracy available in present shoran equipment, formula (1) is used as given, but it was decided to make the refinements available for future use when warranted by improvements in accuracy.

The geometrical reduction requires accurate knowledge of the plane altitude H. Investigation has shown the effect of altitude errors to be most serious when the path length is less than 100 mi; at greater distances the length error remains fairly constant for any given altitude error and has a magnitude of about ten ft for each 200 ft of error in altitude. Use of a pressure altimeter alone may result in an altitude error of several hundred ft in certain cases where meteorological variations are large, although the error may be minimized by careful analysis of available radiosonde data. Altitude accuracy is increased by use of the radio altimeter as a calibration control for the pressure instrument; during operations over water surfaces the radio instrument may be used exclusively. It is believed that by following these procedures, an altitude tolerance of 50 ft or less can be maintained during shoran operational flights.

Method of observation

To measure distance between the two ground stations, A and B, the airborne station is flown at constant ground speed and altitude on a projected course approximately normal to the line AB at a point about midway on the line. The shoran operator maintains the two ground station pulses in constant alignment with the marker pulse on the indicator screen by rotating the goniometer dials. The dial readings are continuously photographed by a motion picture camera at a rate of one frame every three seconds, thus providing a permanent recording of the observations. Each frame records two shoran distances, one to each ground station, the frame number, k, being linearly related to distance along the flight path. The relation between the sum distance, S, and the frame number, k, is a hyperbola with constants depending on the plane altitude and the approximate distance between the ground stations. In practice it has been found desirable to substitute a parabola for the hyperbola in order to simplify the computation; this may be done without significant error since the minimum values of the two curves are almost identical. The general form of the parabolic expression is

$$S - ak^2 + bk - c = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where S = sum of two shoran distances on any frame, k = frame number, and a, b, and c are constants to be determined.

Since the S values contain observational errors, the most probable values for constants a, b, and c are determined by least squares using an observation equation for each frame. Having determined these constants for any single line crossing, the expression is differentiated and equated to zero.

$$dS/dk = 2ak - b = 0$$

whence

$$k = b/2a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The value for k given by (3) is substituted in expression (2) and the corresponding minimum value for S determined. It is pointed out that k is ordinarily a fractional quantity in this operation. To find the geodetic distance between the two ground stations, the integral value of k closest to that given by (3) is used and the shoran distance S_1 to one of the ground stations is read from this frame. The shoran distance S_2 to the second station is then obtained from $S_2 = S_{min} - S_1$. The values S_1 and S_2 are used, together with the ground station elevations and the airplane altitude, to obtain the geodetic distances from the plane to each ground station by the geometrical formula previously described. The sum of these reduced distances is then the observed geodetic distance between the ground stations.

In making the observations, the use of about 15 frames on either side of the minimum point, or 31 in all, has been found satisfactory. By standardizing the number of frames used, certain elements in the least squares solution may be pre-computed and used for all line crossings with a considerable saving in computing time. After the mathematical solution has been made, it is general practice to plot the S value recorded on each frame against the parabola obtained by the least squares solution. This provides a visual representation of the residual obtained for each frame and permits more accurate decisions in cases of possible rejections. A typical minimum-distance curve is illustrated in Figure 1. In this example, the ordinate of the graph represents increment of the sum distances above a reference value of 227.540 mi. The reference value selected is always slightly less than the minimum recorded distance, for convenience in computation and plotting. Several crossings of an individual line are made, and the mean value used as the geodetic distance between ground stations.

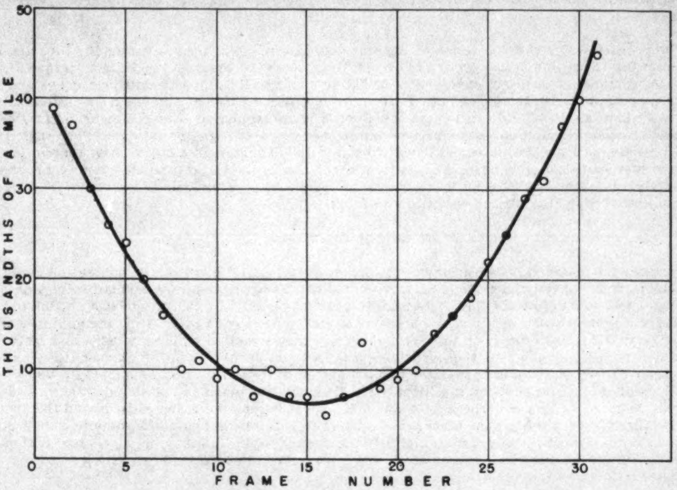

Fig. 1--Shoran line crossing minimum distance curve, Cheyenne-La Junta, May 1, 1946

Computation and adjustment

Revised procedures are required in the computation and adjustment of shoran triangulation. The observed lines may approach 500 or 600 mi in length and many of the assumptions and approximations used in conventional triangulation introduce errors of considerable magnitude in the final results. A new method of least squares adjustment is required in view of the fact that the basic observational data are geodetic distances rather than horizontal angles.

The basic figure used is a triangle whose measured sides are geodetic distances from which the corresponding spheroidal angles may be determined by application of LEGENDRE'S Theorem, provided certain refinements are used in the computation. The first step is the determination of the angles of a plane triangle having sides equal to the geodetic values; any of the standard formulas of plane trigonometry may be used for this operation. Spherical excess is next computed by the usual formula, with the addition of one corrective term, and distributed unevenly among the three angles in accordance with the formula by CLARKE [1880].

$$A_p - A_s = -\epsilon''/3 - [\epsilon''(-2a^2 + b^2 + c^2)]/180R_m{}^2 \quad \ldots\ldots\ldots\ldots\ldots (4)$$

where A_p = plane angle, A_s = spherical angle, ϵ = spherical excess of triangle, R_m = mean radius, and a, b, and c are the triangle sides.

Having determined the spherical angles, a correction may be applied to each angle to reduce to its spheroidal or geodesic value. This correction is given by TOBEY [1928].

$$\tau_A'' = -[\sin(\phi_m + \phi_A)\sin(\phi_m - \phi_A)\epsilon''e^2]/6 \quad \ldots\ldots\ldots\ldots\ldots (5)$$

where $\tau = A_s - A$, ϕ_m = mean latitude of triangle, and e^2 is the minor eccentricity.

The above refinements provide a determination of the geodesic angles within a tolerance of 0.01 sec in a triangle having maximum length of side of 600 mi. In the case of shorter sides and/or greater tolerance in computational error, the corrections given by (4) and (5) may often be neglected.

The precise determination of geographic positions over distances of 500 or 600 mi presents great difficulty from the viewpoint of rapid and accurate computation. The method given by HELMERT, while providing accurate results, is rather forbidding in its complexity, and investigation is under way as to alternate methods with emphasis on applicability to routine computing.

Three methods of accomplishing the least squares adjustment of a shoran scheme have been proposed. These methods are quite different in approach and each has proved satisfactory in computational tests. No decision has been made as to the final method or methods to be adopted, pending further study of practical considerations involved. When a quadrilateral is determined by direct measurement of its sides only, one condition equation results as contrasted with four in the case of horizontal angle measurement. Considering one side of the quadrilateral to be fixed in position, azimuth, and length, the ratio of conditions per new station determined is thus seen to be one to two when the sides alone are measured. This ratio is improved by the substitution of a five-sided figure with all diagonals observed; the condition-station ratio then becomes one to one, making the figure comparable in strength to the conventional single triangle with all angles observed. Accordingly, the five-sided figure has been adopted as the basic unit in the layout of proposed triangulation.

Results of accuracy tests

Table 1 gives results obtained during recent field tests conducted by the 311th Reconnaissance Wing in Colorado, Kansas, Nebraska, and Wyoming. Ground stations were established at United States Coast and Geodetic Survey first-order triangulation points, and geodetic distances obtained by inverse computation were used to evaluate accuracy of the shoran measurements.

Table 1--Results of shoran accuracy tests in Colorado, Kansas, Nebraska, and Wyoming, 1946

Geodetic line	Number of crossings	Observed distance	True distance	Observed minus true distance	Proportional error
		mi	mi	mi	
La Junta-Garden City	18	148.5322	148.5395	- 0.0073	1/ 20,300
Cheyenne-Imperial	17	173.7443	173.7471	- 0.0028	1/ 62,100
Imperial-Garden City	17	181.3687	181.3694	- 0.0007	1/ 259,100
La Junta-Imperial	44	198.7188	198.7099	+ 0.0089	1/ 22,300
Cheyenne-La Junta	47	227.2917	227.2868	+ 0.0049	1/ 46,400
Cheyenne-Garden City	19	308.5250	308.5252	- 0.0002	1/1,542,600

It is difficult at this stage to estimate the ultimate accuracy to be obtained by the shoran method. The equipment was originally designed to produce a degree of precision somewhat lower than that required in geodetic operations, and although many refinements have been made to date, further progress is anticipated. As the ultimate in instrumental accuracy is approached, propagation uncertainties will become better defined in magnitude and may well prove the limiting factor in distance determination by shoran.

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CLARKE, A. R., Geodesy, pp. 46-48, 1880.
TOBEY, W. M., Geodesy, Geodetic Survey of Canada, Pub. no. 11, p. 68, 1928.

U. S. Coast and Geodetic Survey,
Washington, D. C.

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NOTE ON THE EARTHQUAKE AND SEISMIC SEA WAVE OF APRIL 1, 1946

Ralph R. Bodle

The earthquake of April 1, 1946, was one of the very few Aleutian earthquakes whose instrumental epicenter may be checked against surface effects. Its magnitude was just under the lower limit of a major earthquake. Early seismographic data came from the United States, Alaska, and Hawaii. Some uncertainties were involved in the interpretations, which could not be appraised until the records were received, the difficulty being largely the result of heavy microseismic activity.

Examination and correlation of available data were completed about the middle of May, 1946, and resulted in a reasonably dependable position near 53°.5 N, 163°W, with origin time of 12^h29^m, GCT. The depth of focus was near normal. The epicenter is based on the normal depth tables of GUTENBERG and RICHTER.

Data from European and Russian stations still are not available (May 20, 1946) and may later furnish grounds for a minor change. Data from four Japanese stations were received through the headquarters of the 20th Air Force. They proved to be inaccurate, probably due to time-control problems.

Through cooperation of the United States Navy and the United States Coast Guard, copies of dispatches on the earthquake were furnished to the United States Coast and Geodetic Survey. It must be assumed that this information is general. In fairness it should be stated that the messages were not prepared for scientific purposes. They may not, therefore, be as complete as might be desired, but they do furnish more information than has been available for any previous earthquake in the Aleutian area.

The following is a statement of the general check on the instrumental results based on the dispatches and experience with other earthquakes.

It was reported that some 60 aftershocks were felt at Ikatan. A press release stated: "In the Cold Bay region and at Sand Point tremors were felt at irregular intervals." Cold Bay is just east of Ikatan. Ikatan is about 85 miles north of the instrumental epicenter, while Sand Point is 190 miles northeast.

By way of comparison of central area surface effects for various earthquakes it was found that the instrumental epicenter for the Cornwall, Ontario-Massena, New York earthquake of September 5, 1944, agreed very well with the center of maximum intensity. Many aftershocks occurred, none of which appeared to center more than a very few miles outside the epicentral area between the two towns, which are about ten miles apart.

Another example of aftershocks in the epicentral area is the shock of July 22, 1937, which was destructive at Fairbanks, Alaska. Details may be found in Coast and Geodetic Survey Serial Publication no. 619, United States Earthquakes, 1937, which states that surface cracks were noted about 16 miles from the instrumental epicenter position, also that several hundred aftershocks were recorded, some being felt 125 miles from the epicenter. Instrumental data indicated the aftershocks centered from 29 to 39 miles from the College, Alaska, seismograph while the main shock was about 30 miles distant.

In both of the above cases the minor aftershocks occurred within 15 or 20 miles of the instrumental epicenter. The possible error in the epicenter position given in this paper for the Aleutian shock of April 1, 1946, is considered to be well within this limit.

From this, one would not expect so many aftershocks at Ikatan, 85 miles away. It is not known whether aftershocks were as numerous on Sanak Island, some 60 or 70 miles from the epicenter and south of Ikatan. Twenty-six aftershocks were reported at Chignik, about 265 miles northeast. However, no rational basis has been found to justify any appreciable change in the instrumental epicenter even though numerous aftershocks were observed at abnormally distant points. The situation is not easily explained. The active fault may run north and south and may account for the difference in the position of aftershocks at Ikatan and the instrumental epicenter. Also the apparent difference may be due to geologic formations, especially if Ikatan is on deep silt. The Chignik shocks, because of the distance, may not have been directly related to the main shock.

Results of tidal studies tend to confirm the epicentral position, since a 20-foot wave was reported at Sanak ten minutes after the main shock. The Navy-Coast Guard dispatches are not clear regarding destructive sea action at Ikatan. It is felt that perhaps no destructive wave effects occurred there. Information has been requested. The wave reportedly arrived at Scotch Cap about one hour after the earthquake. The recorded arrival times of the waves at 25 tide stations on the Pacific coast of North America are in excellent agreement with arrival times based on water depths as computed by the Division of Tides and Currents of the United States Coast and Geodetic Survey.

As a result of the data made available for this earthquake, it is felt that the problems involved in the study of all earthquakes in the Aleutians are more clearly defined than ever before, due in large measure to the data received from the Armed Services. Again the need for a seismograph station in the area has been emphasized. Certainly no sound basis for determining the cause of seismic sea waves can be found unless epicentral positions are made available with an accuracy that will permit definite association with features of the ocean bottom.

[See also Papers in Oceanography in this issue for a paper by C. K. GREEN entitled "The Seismic Sea Wave of April 1, 1946, as recorded by tide gages"--Ed]

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

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MICROSEISMS CLASSIFIED ACCORDING TO TYPE OF STORMS

Marion H. Gilmore

Abstract--The purpose of this paper is to present certain technical details involved in a proper interpretation of dominant microseisms recorded in the Caribbean. Twelve figures are given that show microseisms produced by hurricanes, cold fronts, thunderstorms, fair weather, and artificial vibrations. These are classified and listed in Table 1 according to type, period, amplitude, form, and duration.

Microseismic research work carried on by the United States Navy in the Caribbean during the past two years has definitely proved that dominant microseisms of two to seven second periods originate in or around the center of atmospheric disturbances. This is especially true when the disturbance is a hurricane. Present data indicate that some force within the storm has sufficient energy to cause the ocean bottom to vibrate. The more or less regular oscillations thus produced are called microseisms. They are transmitted through the outer fifteen to twenty kilometers of the Earth's crust to the various seismographs in the area and recorded on them.

Dominant microseisms, therefore, are directly connected with changes in the atmosphere, which is never still. On the contrary, it is always on the move and is sometimes violently disturbed. The various atmospheric changes cause microseisms that differ in type, period, amplitude, form, and duration. The mechanics by which microseisms are produced by storms are not definitely known. In some manner the energy from storms is transmitted directly to the bottom of the ocean and then, in the form of microseisms, through the ground to the seismograph station. However, any noticeable change in the weather within 300 mi of a microseismic seismograph station will usually be recorded as some definite type of microseism. For major well-developed hurricanes and severe extra-tropical lows this maximum distance may be increased to nearly 2000 mi. The actual distance from a seismograph station that a storm can be detected is dependent on the severity of the atmospheric change, its position in relation to very shallow water, and deep discontinuities in the Earth's crust.

Several distinct types of microseisms recorded in the Caribbean during the past two years are easily recognized and can be classified into certain definite groups. Each group is associated with a particular type of atmospheric disturbance. A properly-trained and experienced observer can now analyze a record of dominant microseisms made at any good Caribbean station and determine, to a great extent, the type of severe atmospheric disturbance that produced it.

The Sprengnether galvanometric recording seismographs were used throughout the Hurricane Microseismic Research Project and proved to be very satisfactory for this type of work. The instrumental periods used were from five to seven seconds. The instruments had a maximum magnification of 5000 and a variable drum speed of 1/2 to 4 mm/sec. The following figures represent the various types of microseisms recorded during two years of research work. They differ in type, period, amplitude, and form. Each trace represents from six to twelve minutes duration, depending on the drum speed. Complete information as to drum speed, station, and date of record is given under each figure.

The microseisms at the beginning of this record show an increase in amplitude and a slightly longer period (about four sec) than those recorded the day before at Guantanamo Bay, Cuba, and this trend continues for several days (see Fig. 1). They are less confused in shape and are gradually building up into more definite and sharper peaks near the end of the record. When a hurricane is developing or passing near a seismograph station, the microseisms always get larger and develop into well-shaped peaks.

The record shown in Figure 2 was made two days later. Regular and well-formed microseismic peaks have already developed. The amplitude is large and the period has increased to five sec. When microseisms increase in amplitude the period usually lengthens, although this is not always true.

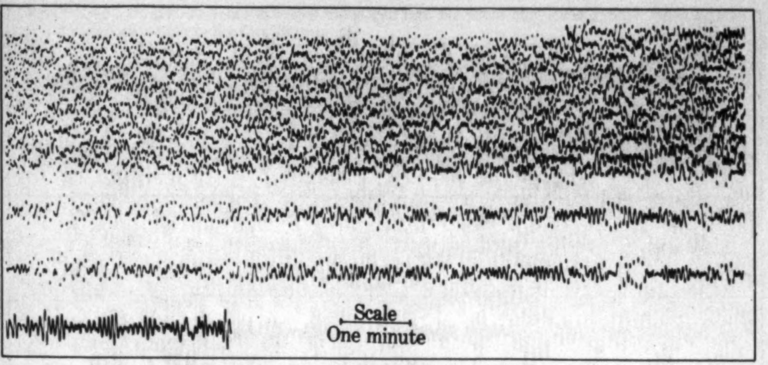

Fig. 1--Microseisms showing start of hurricane 525 mi southwest, Guantanamo Bay, Cuba, 13-14 October 1944

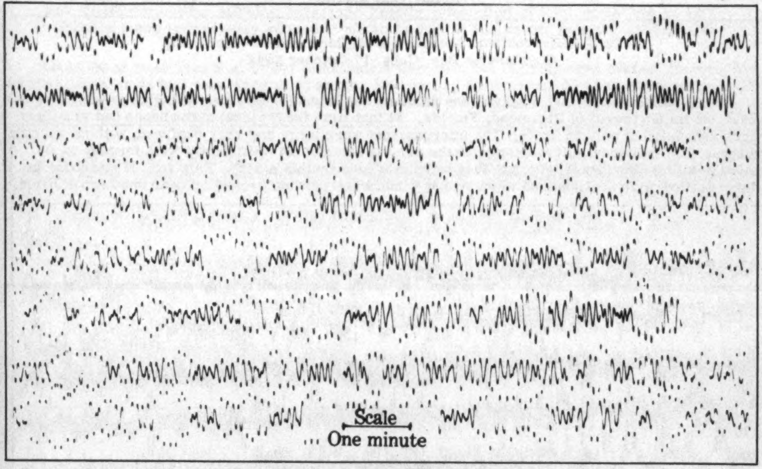

Fig. 2--Microseisms showing hurricane 500 mi west southwest, Guantanamo Bay, Cuba, 16 October 1944

The record shown in Figure 3 was made one day later. These dominant microseisms are very regular and extremely well-formed into maximum peaks and may be considered typical microseisms caused by a hurricane. The period has increased to six sec. There can be no reasonable doubt that the microseisms shown in the first three figures were caused directly by the October 1944 hurricane. Every direction obtained from the tripartite seismograph station indicated the microseisms were coming directly from the storm area. These directions always changed as the storm moved forward in its path.

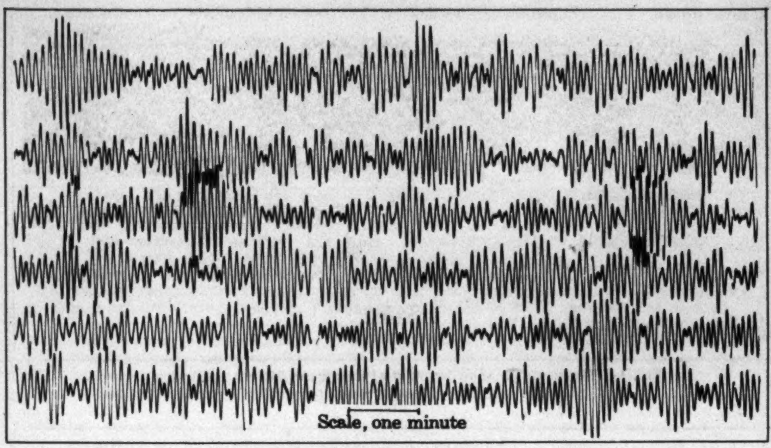

Fig. 3--Microseisms showing severe hurricane 550 mi west, Guantanamo Bay, Cuba, 17 October 1944

These microseisms (see Fig. 4) were made by the June 1945 tropical disturbance when it was about 325 mi northwest of Richmond, Florida. At that time the tropical disturbance had maximum winds estimated at only 55 knots. The microseisms were large and very confused, with no specific pattern. The individual microseismic peaks are too few and not sufficiently well-formed to be called a definite hurricane type, yet they were produced by this storm. This type of microseism was recorded often at Richmond when strong winds were blowing around or near southern Florida.

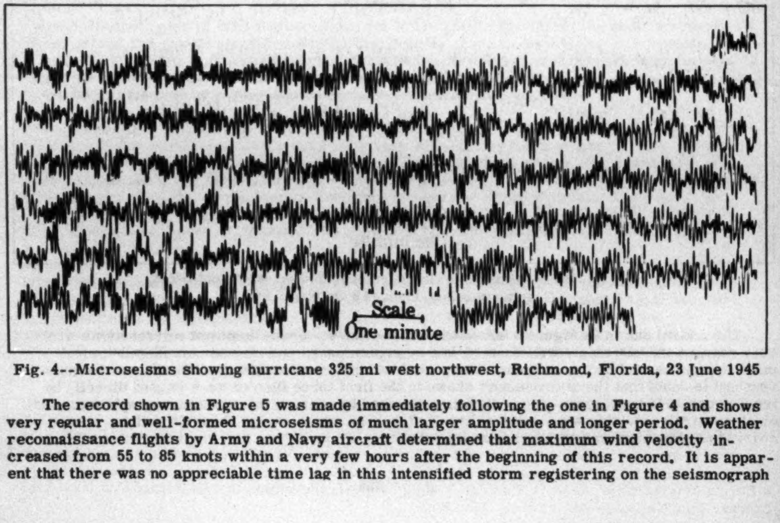

Fig. 4--Microseisms showing hurricane 325 mi west northwest, Richmond, Florida, 23 June 1945

The record shown in Figure 5 was made immediately following the one in Figure 4 and shows very regular and well-formed microseisms of much larger amplitude and longer period. Weather reconnaissance flights by Army and Navy aircraft determined that maximum wind velocity increased from 55 to 85 knots within a very few hours after the beginning of this record. It is apparent that there was no appreciable time lag in this intensified storm registering on the seismograph at Richmond. The microseisms speedily developed into the usual hurricane pattern found associated with all hurricanes in the Caribbean.

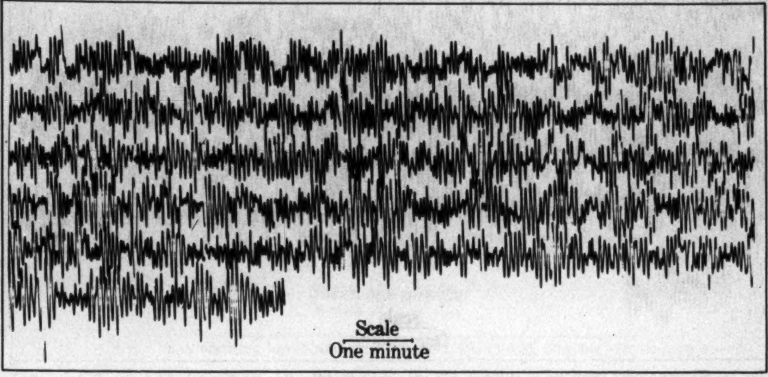

Fig. 5--Microseisms showing hurricane greatly intensified 325 mi northwest in Gulf. Record made immediately after that shown in Fig. 4, Richmond, Florida, 23 June 1945

About 20 hr later (see Fig. 6) the same storm was centered entirely over central Florida, but its maximum winds had decreased to 40 knots. The record shows much smaller microseisms than in Figure 5, yet they are very regular and have excellent buildups into maximum peaks.

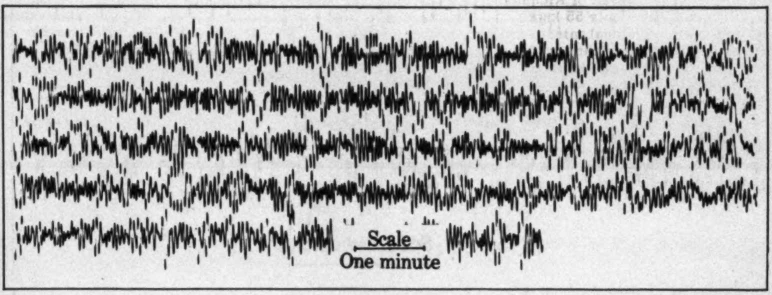

Fig. 6--Microseisms showing hurricane 300 mi north over land, Richmond, Florida, 24 June 1945

The microseisms shown in Figure 7 were made one day later, when the hurricane had moved into the Atlantic and maximum winds had increased to 65 knots. The microseisms are large and well-formed, even though the storm was more than 475 mi away.

The extremely large microseisms shown in Figure 8 were recorded about three hr before the September 1945 hurricane passed over the seismograph station at Richmond, Florida. They are well-formed for such large amplitudes and indicate a great amount of energy was being expended through the water and onto the ocean bottom. The maximum wind speed was 100 knots when this record was made.

The following day the hurricane was over central Florida (see Fig. 9). Both the hurricane intensity and the microseismic activity had greatly decreased. However, the microseisms were well-formed and definitely indicated a hurricane. This record and that in Figure 6 were made when two different hurricanes were over Florida. It would appear, therefore, that hurricanes do (at times) produce microseisms when entirely over land.

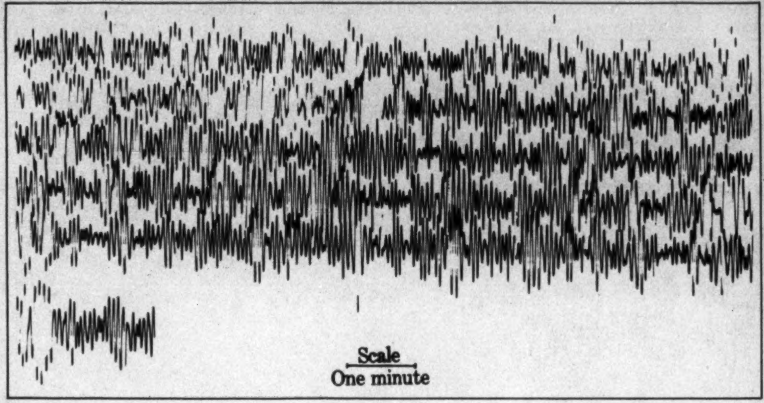

Fig. 7--Microseisms showing hurricane 475 mi north in Atlantic, Richmond, Florida, 25 June 1945

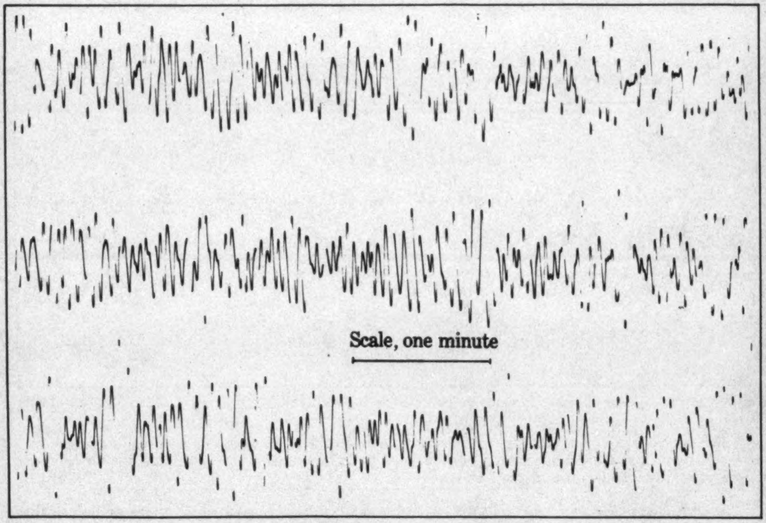

Fig. 8--Microseisms made three hr before hurricane passed over station, Richmond, Florida, 15 September 1945

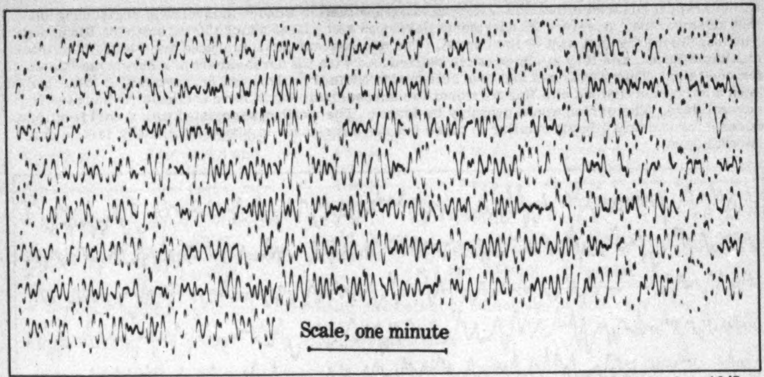

Fig. 9--Microseisms showing hurricane over Florida, Richmond, Florida, 16 September 1945

Two days later the hurricane was about 750 mi north in the Atlantic (see Fig. 10). These microseisms are well-formed and continue to show definite types.

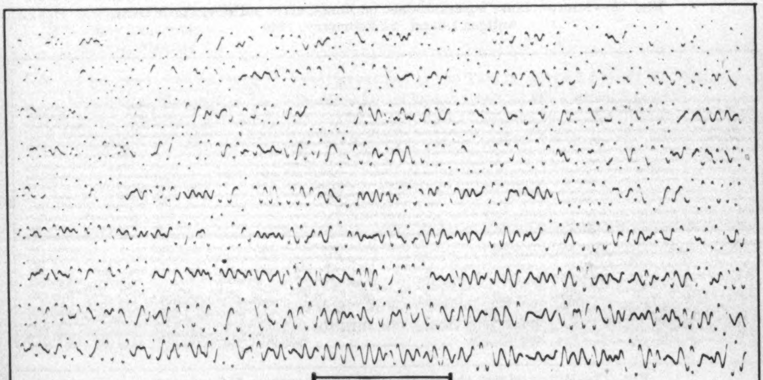

Fig. 10--Microseisms showing hurricane 750 mi north, Richmond, Florida, 18 September 1945

The microseisms shown in Figure 11 were made in February 1946 at Antigua Island. The peculiar, extra-long period vibrations were produced by a strong wind blowing against the house where the seismometer was temporarily installed. Normal microseisms are superimposed on the larger curves. This type of extremely irregular microseisms could never be confused with dominant hurricane microseisms even though the amplitude is large.

The record of Figure 12 is important because it shows two distinct types of microseisms. Those recorded during the first four hours are normal microseisms, and this type is recorded at all times when there is no abnormal weather of any kind near the station. It has been demonstrated through two years of research that it is impossible for any type of severe weather to develop at or within several hundred miles of a microseismograph station without immediately registering on that seismograph. A severe thunderstorm developed and passed about 150 mi south of Richmond, Florida, during the last part of the record. The microseisms thus produced are well formed into maximum peaks, and they might possibly be confused with the development of a hurricane except for one thing: They developed and then returned to normal in about six hr; whereas, if there had been a hurricane instead of a thunderstorm the microseisms would have continued to increase for several days. The period would probably be longer. The weather associated with a cold front produces microseisms slightly similar to these but more irregular in shape and usually lasting for several days.

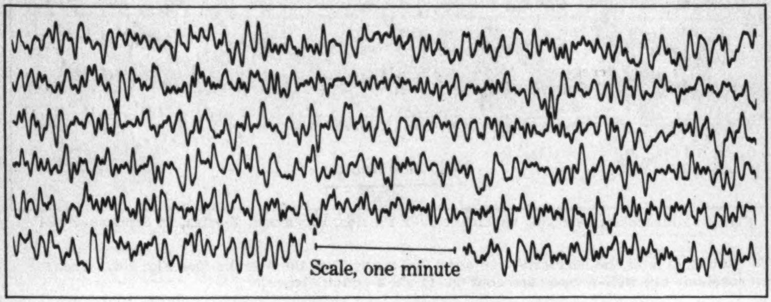

Fig. 11--Microseisms superimposed on long-period building vibrations, Antigua Island, 14 February, 1946

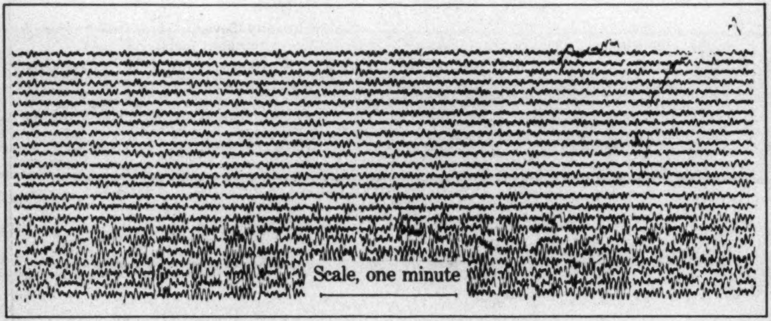

Fig. 12--Microseisms showing severe thunderstorm 150 mi south, Richmond, Florida, 24 August 1945

These twelve figures show several definite types of microseisms produced in the Caribbean from 1944 to 1946. They contain certain characteristics which may be used to identify microseisms caused by hurricanes, cold fronts, and normal weather. The first ten figures show microseisms having definite beats, that is, buildups into sharp maximum peaks that are definitely caused by hurricanes. The dominant peaks can always be separated from the irregular microseisms produced by strong wind from nearby places and from artificial vibrations, such as shown in Figure 11. Table 1 has been prepared to summarize these data into usable information. It represents a first attempt to correlate and tabulate certain hurricane-microseismic data obtained in the Caribbean during two years of research. The figures are only approximations and are subject to later revision. Therefore, the table will undoubtedly be modified and improved when additional data become available from this season's work.

Table 1--Characteristics of microseisms

Kind of weather	Type	Period	Amplitude (times normal)	Form	Average duration of storms
		sec			
Hurricanes	Well-formed peaks, good buildups	2 to 7, slow change	3 to 30	Very regular	3 to 10 days
Cold fronts	Fair peaks and buildups	1 to 4, rapid change	3 to 12	Regular to irregular	1 to 3 days
Thunderstorms	Good peaks, fair buildups	1 to 3, nearly constant	3 to 5	Regular to irregular	3 to 7 hours
High winds	No definite peaks, irregular	1 to 10 rapid change	3 to 10	Very irregular	1 to 10 days
Fair	No definite peaks, irregular	Irregular	Normal[a] 1.5 to 2.5 mm	Very irregular	1 to 15 days

[a]Normal average amplitude is dependent on location of station and on type of foundation

Acknowledgments

The author's thanks and appreciation are due the United States Coast and Geodetic Survey for help with printing titles for the twelve figures; to H. T. ORVILLE and WILLIAM LOVELAND, USN, for general supervision of the Hurricane Microseismic Research Project and for specific assistance and excellent cooperation in carrying on the work; and to L. A. SCHAAL, USNR, and MARY FLEMING for assistance in the final preparation of this paper.

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REDUCTION OF WIND DATA

Ronald L. Ives

(Published by permission of Chief of the Chemical Warfare Service, United States Army)

Abstract--Various derived wind functions are here defined; methods of derivation outlined; a complete wind record reduced, as a sample demonstration of the outlined methods; and various applications of the derived functions briefly mentioned.

Introduction--Field investigation of wind behavior, as applied to chemical and engineering problems, disclosed that the existing terminology suffered from obsolescence and acute nebulosity. So great is the lack of rigor in the commonly-used definitions that the data presented in accord with them differed, in some instances, by 180° from that shown by other field evidence.

In many instances these discrepancies between reported wind behavior and field evidence of wind work have been attributed to incompetent observing or inadequate equipment. Field checking in the Skull Valley Area (Utah), where discrepancies are particularly marked, disclosed that the observations were of a high order of accuracy, that the field evidence was, likewise, accurately reported, and that the discrepancy was due solely to inadequate terminology.

Table 1--Copy of an observer's report, showing relation of wind observations, Oblivion Junction[a], March 1, 1944
(Other meteorological data are usually entered on the same form)

Time, MWT	Source	Speed
		mi/hr
00^h00^m	SE	5
01 00	SSE	6
02 00	SE	2
03 00	SE	3.5
04 00	SE	7
05 00	NW	4
06 00	SW	3
07 00	SE	5
08 00	NNE.	4
09 00	N	3
10 00	NW	3
11 00	N	7.5
12 00	NE	6
13 00	ENE	4
14 00	NNW	2
15 00	NW	15
16 00	NNW	10
17 00	NNW	5
18 00	NNW	5
19 00	N	12
20 00	SE	1
21 00	W	3
22 00	WNW	6
23 00	NNW	3

[a] Latitude 40°09'15" north, longitude 113° 11'08" west; elevation 4330 feet above mean sea-level; additional data, not pertinent to this study, are normally placed to right of wind figures by observer.

To correct this prevalent difficulty, a number of derived wind functions are here redefined, and methods of computing them are outlined. It is not expected that this outline will fill all needs, or be the one finally adopted; but it appears probable that these redefinitions will reduce the present difficulties resulting from overloose terminology. (Whenever a technical report concerns more than one science, it is important that the terms used be specifically defined, either by reference, or by included definition, to reduce terminological confusions. To cite an extreme example, the term sublimation has one meaning for a meteorologist, and an entirely unrelated and different one for a psychologist.)

Raw data--The term raw data, as here used, refers to the observer's report. In most instances, this includes the time, the wind direction (source of wind, not destination), and the wind speed, as measured by one of several methods. Customarily, the wind speed reported is the speed measured during one minute. Only a few stations report travel, which is the total wind mileage during the hour.

Raw data are shown in Table 1, which is a copy of an observer's report. (For reasons of security, the geographical name entered on this report has been altered.) Although it is not customarily done, these reports would be greatly improved if the type of instrument used, the speed-timing method, and the height of the anemometer above the ground were entered upon them.

Wind roses--A wind rose is a polar graph, in which the function r is some scalar wind function, and θ is the azimuth of that function. Customarily shown by means of wind roses are wind frequency--the number of regular reports, shown by directions, in an observing period (number of hourly reports, per direction, per day of 24 hours, for example)--and wind travel--the number of miles of wind, shown by directions, in a like interval. A wind-frequency rose, based on Table 1, is shown in Figure 1. A mileage rose, based on the same data, comprises A of Figure 2. It should be noted that, in most instances, the mileage shown in charts of this type is extrapolated mileage (to be discussed later), not measured travel.

Where a number of functions must be derived from raw data, a collation table, as in Table 2, in which the reported wind speeds are classified by direction, will be found helpful.

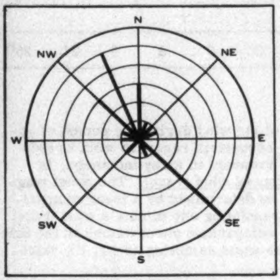

Fig. 1--A wind-frequency rose based on data of Table 1 (Each circle represents one hourly report)

Maximum wind speed--Maximum wind speed, when determined solely from the observer's report, is the highest speed included in the report. This, in Table 1, is 15 mi/hr, from NW, at 15^h00^m, and is found by direct inspection of the data sheet.

In a few of the more advanced meteorological stations, chart-recording instruments, or special maximeters, give a better indication of the maximum wind speed. This, in general, is reported as a direction, a speed, and the time of occurrence. Rarely, the duration of the speed maximum is also reported.

Minimum wind speed--Minimum wind speed is the lowest speed reported by the observer. This, from inspection of Table 1, is found to be SE, one mi/hr, at 20^h00^m. Minimum speed is normally reported as a direction, a speed, and the time of occurrence. When minimum speed is zero, the wind has no direction, and the report then reads 0 at (time).

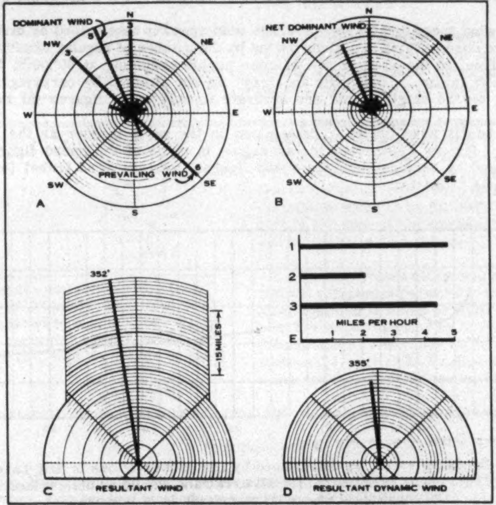

Fig. 2--Chart of various derived wind functions (All figures derived from raw data of Table 2)

Table 2--Collation table, to assist in deriving wind functions from raw data

Location: Oblivion Junction Date: March 1, 1944 Function: S

Source															
N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	**S**	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**
3	4	6	4	0	0	5	6	0	0	3	0	3	6	4	2
7.5						2								3	10
12						3.5								15	5
						7									5
						5									3
						1									
22.5	4	6	4	0	0	23.5[a]	6	0	0	3	0	3	6	22	25[b]

[a] Prevailing wind [b] Dominant wind

Total wind travel--Total wind travel is the total travel of the wind during the period of observation. This is commonly determined by assuming that the respective recorded wind speeds are the actual hourly wind travel. What is actually dealt with, however, in many instances, is extrapolated wind travel, which may differ markedly from measured wind travel. The exact magnitude of the error depends upon local wind structure, and can be determined by a local comparison study. Magnitude of the sampling error, introduced by extrapolating one minute's wind travel by a factor of 60, as determined from more than 5000 hours of comparison observations in the Salt Lake Desert, is shown in Figure 3. As all areas do not have the same sampling error, its value must be determined by local observations.

Reported wind travel should be further described as extrapolated (customary method) or measured (preferred method, not customary).

Total wind travel (extrapolated) for March 1, 1944, as found from Table 1 is 115.0 miles.

Average wind speed and travel--Average wind speed is determined by dividing the sum of the regular speed observations in a given period by the number of regular observations in the same period. This, in the case of the 24-hour period beginning at 00^h00^m, March 1, 1944, is (115/24) or 4.79 mi/hr. "Scientific accuracy" is not attained by carrying this out to 4.791666 mi/hr, as the original data are accurate to only three figures (at their very best).

Average hourly wind travel is determined in the same manner as the average wind speed, the travel figures being used for averaging in place of the speed figures. As travel is commonly found by extrapolating the speed figures, average wind travel (extrapolated) for March 1, 1944, is 4.79 mi/hr.

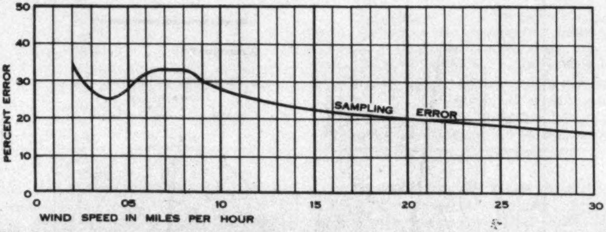

Fig. 3--Sampling error, as determined by field observations in Salt Lake Desert (This error is not same for all areas and should be determined by local tests where its magnitude is of importance)

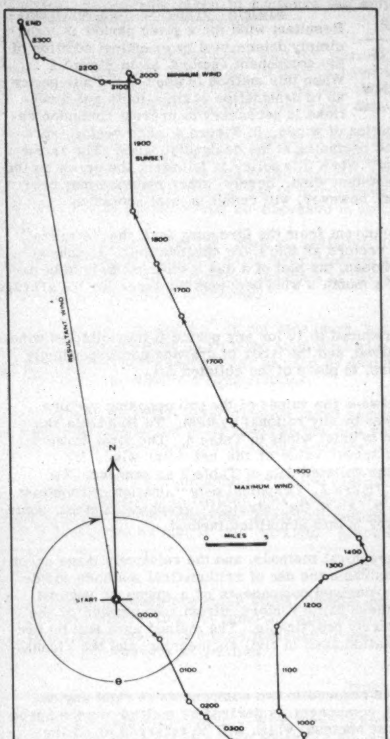

Fig. 4--Graphical summation of vectorial wind reports to determine resultant wind (Vectors compared to extrapolated travel during hours beginning at time indicated; arrows on vectors point to source of wind)

Prevailing wind direction--Prevailing wind direction, as commonly defined, is the direction from which the wind most frequently blows. (A typical definition, given by TREWARTHA [p. 84, 1943] is, "When a wind blows more frequently from one direction than from any other it is called a prevailing wind.") This is most conveniently found from inspection of the observer's report or from the wind-frequency rose (Table 1 or Fig. 1). When a wind-frequency rose is not drawn, the same determination can be made from the collation table (Table 2).

Dominant wind direction--The dominant wind direction is the direction, during any period of observation, from which the most wind blows. This figure is conveniently determined by inspection of a wind-travel rose as in Figure 2A where it is found to be NNW. This may be found also from the collation table (Table 2).

As the dominant and prevailing wind directions are the same in many areas, the two terms have been used interchangeably in numerous instances without introducing serious difficulties.

"Floored" winds--When winds below a definite speed have no effect on the problem under consideration, the prevailing and dominant winds are sometimes determined from the remaining data. These functions are then "floored" at a definite wind speed. Examples of "floored" winds are given in Table 3, all data being computed from that in Table 1.

It will be noted that, when the total number of observations is small, as in Table 1, the prevailing wind will often "drop out" or become ambiguous, as the floor is raised.

Axis of maximum travel--The axis of maximum travel is the axis along which the sum of the absolute values of the wind speeds is greatest. This figure is most easily determined by inspection of the wind-travel rose of Figure 2A, in which the axis is found to be SE-NW. Travel along this axis is the sum of the southeast and northwest winds, which is 48.5 miles.

The net travel along this axis is the arithmetical difference between the travels in each direction, and is found by subtracting the northwest travel (designated by source) of 22 miles, determined by reference to Table 2, from the southeast travel of 23.5 miles as found from the same source. The net travel is 1.5 miles.

This determination can also be made from the net wind rose (Fig. 2B) to be described later.

Resultant winds

Definition--Resultant wind is the vector sum of the reported winds during a given period. In many instances, with present methods of reporting, this will actually be the vector sum of the extrapolated wind travels, rather than the actual travels.

Table 3--Examples of "floored" wind-functions

Floored at mi/hr	0	5	10	15
Prevailing wind	SE	SE or NNW	. . .	. . .
Dominant wind	NNW	NNW	NW	NW

"Straight" graphical determination--Resultant wind for a given period is most simply determined by graphical addition of the component vectors, as in Figure 4. When this method is used, a definite policy as to designation of time-units and directions is necessary to prevent confusion resulting from the conventional "backwards" designation of winds. In Figure 4, each vector represents the extrapolated wind travel during the period beginning at the designated time. The arrow on each vector points toward the source of the wind. When this policy is followed, the arrow on the resultant vector points toward the source of the resultant wind. Several other methods may be used with equal success. Lack of a definite system, however, will result in total confusion.

Simplified graphical method--As should be apparent from the foregoing text, the "straight" graphical method requires the plotting of as many vectors as there are observations. In consequence, if a scale convenient to the draftsman is chosen, the plot of a day's wind is likely to be as large as a standard drawing-board, and the plot of a month's wind becomes too large for the average meteorological office.

The number of vectors to be plotted may be reduced to 16 for any period if the collected wind data of Table 2 are plotted. This figure may be halved, and the labor of drafting correspondingly reduced, if the net axial winds are plotted as vectors, in place of the collated data.

Net axial wind is the numerical difference between the values of the two opposing vectors along any axis, sign and designation being determined by any rational system. To illustrate the method, the collected data of Table 2 are converted to axial winds in Table 4. The first three columns give the derivation, axial designation, and travel value of the net axial winds for March 1, 1944, using the raw data of Table 1, and the collated data of Table 2 as sources. Net axial winds, plotted as a wind rose, comprise B of Figure 2. Graphical determination of resultant wind, by use of net axial winds, is shown in Figure 5. As in the "straight" graphical method, some rational system of designating direction is necessary in this simplified method.

Arithmetical methods--The unwieldiness of graphical methods, and the relatively large error inherent in even the most careful drafting, make desirable the use of arithmetical methods for determining resultant winds. Because the sum of like-derived components of a group of vectors equals the like-derived components of the sum of these same vectors, direct computation of the direction and magnitude of the resultant wind is entirely practicable. The method used will be recognized as the "latitudes-and-departures" computation used in civil engineering, and the "transformation of coordinates" used by mathematicians.

In the arithmetical method, each wind vector is reduced to two components at right angles. The ordinate, which will be referred to as the North component, is derived by multiplying the speed (or travel) value by the cosine of the azimuth, and the abcissa, which will be referred to as the East component, is found by multiplying the same speed figure by the sine of the azimuth. Arithmetical signs must be preserved throughout.

Table 4--Derivation of axial winds and axial vectors

Derivation	Axial designation	Travel value	θ	$\underline{N} = S \cos \theta$	$\underline{E} = S \sin \theta$
		mi.	°	mi.	mi.
N-S	N	22.5	0	22.5	0.0
NNE-SSW	NNE	4.0	22.5	3.7	1.5
NE-SW	NE	3.0	45	2.1	2.1
ENE-WSW	ENE	4.0	67.5	1.5	3.7
E-W	E	-3.0	90	0.0	-3.0
ESE-WNW	ESE	-6.0	112.5	2.2	-5.5
SE-NW	SE	1.5	135	-1.1	1.1
SSE-NNW	SSE	-19.0	157.5	18.5	-7.1
		Totals		49.4	-7.2

Square root of sum of squares of totals = $(2440 + 51.7)^{1/2} = \sqrt{2491.7} = 49.9$ miles = length of vector arc tangent of azimuth = (E/N) = (-7.2/49.4) = -0.1459; azimuth = 352°

The sums of the north and east components are taken separately. The square root of the sum of their squares is the length of the resultant, and hence the value of the resultant wind in the same units as the original figures. The arc tangent of the azimuth is found by dividing the sum of the East components by the sum of the North components. The actual value of this angle is found from a table of natural tangents, care being taken to preserve the arithmetical signs of the components, so that the correct azimuth is determined.

The value of the resultant wind for March 1, 1944--49.9 miles from 352°--as found by this method, is shown in Figure 2C. It may be noted that the number of trigonometric computations required may be markedly reduced, at no loss in inherent accuracy, by use of net axial wind data, in place of collated azimuthal winds, or of raw data.

Choice of methods--Six methods of determining resultant wind--three graphical, and three arithmetical--have been presented. Accuracies of the methods in each group are substantially identical; all methods are inherently accurate enough for most work, as the method errors are very much smaller than those due to instrumental shortcomings, observational errors, and extrapolation (or sampling) error as discussed in an article by R. L. IVES and E. L. KROONA [1946].

Where a "running fix" must be available, the "straight" drafting method (Fig. 4) is usually preferable, as it permits a quick determination of the current resultant wind, from any preceding time on the plot. This method, however, is likely to be unwieldy, particularly when a large number of observations is concerned.

When a "running fix" is not necessary, but graphical determination is preferred, the simplified plot, based either on collated azimuthal winds (Table 2), or net axial winds (Table 4, Fig. 5), is preferable. This method can be used by assistants who are likely to become hopelessly confused with trigonometric computations.

Where graphical determination is not necessary, as in most climatic and engineering work, computation, using net axial winds as the data source, is the most expeditious method. Here, most of the computation consists of simple addition, suitable for machine work by semi-skilled help.

Experience accumulated during the reduction of several years of wind records indicates that, when the computer has reached maximum skill, the simplified graphical method is more than twice as fast as the "straight" graphical method, and that computation from net axial winds is about five times as fast as the "straight" graphical determination.

Ambient winds

Ambient winds are those which "cancel out" during the period of observation. Their value is found by subtracting the resultant wind from the total wind for the same period. The ambient wind, in many areas, is a good measure of the magnitude of local air circulation. Ambient wind, for March 1, 1944, is 65.1 miles.

Dynamic winds

Preliminary discussion--Wind force, which is a direct measure of its ability to do work (or damage), varies directly as the square of the wind speed, a quantity normally measured by standard instruments. As there are no standard instruments in general use which measure wind force, or which integrate this figure to give hourly, daily, or directional equivalents, this figure must be computed from available data. There being no simple direct method of integrating wind force, a somewhat empirical equivalent must be adopted for practical use.

Dynamic wind, computed by taking the square root of the sum of the squares of the hourly speed reports, seems the best compromise figure for use with existing measuring equipment. Dynamic wind, as here determined, is the wind speed, which, continued for one hour, has the same work-doing ability as the wind for the entire period under consideration.

Total dynamic wind for a given period is the square root of the sum of the squares of the individual reported speeds during the period. In most instances, total dynamic wind is synonymous with dynamic wind. The total dynamic wind for March 1, 1944, computed on this basis, is 35.5 miles (continued for one hour).

It should be noted that dynamic wind is an empirical measure, entirely accurate when the wind speed remains constant during the whole hour following speed measurement. The probable error becomes quite great with gusty winds of low average speed.

Average dynamic wind is the dynamic wind which, blowing steadily throughout the entire reporting period (such as a day of 24 hours) has the same work-doing ability as the reported wind. This figure for March 1, 1944, as determined from the raw data of Table 1, is 6.85 mi/hr.

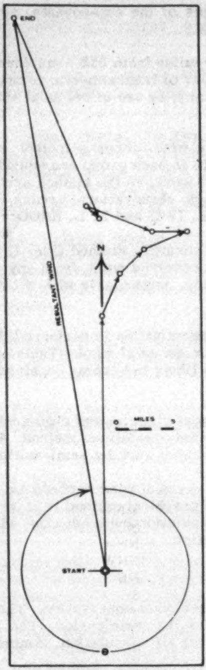

Fig. 5--Graphical determination of resultant wind by use of net axial winds (arrows point to source of wind)

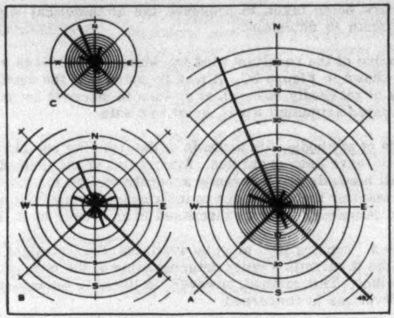

Fig. 6--Wind roses for 22^h00^m, March 1, 1944 (Total travel by azimuth is shown at A, wind frequency by azimuth at B, and average speed by azimuth at C)

Average dynamic wind is found by dividing the sum of the squares of the individual speed reports by the number of such reports, and then taking the square root. The same figure can be obtained by dividing the total dynamic wind by the square root of the number of observations.

Resultant dynamic wind is the single wind which, blowing steadily for one hour, has the same net work-doing ability as the reported winds for the period. Resultant dynamic wind is the power analogue of resultant wind.

Resultant dynamic wind is determined by taking the vector sum of the individually reported dynamic winds. These are found from the speed reports (Table 1) by retaining the azimuth, and squaring the speeds. The azimuth of the resultant of these vectors is the azimuth of the resultant dynamic wind; while the square root of the length of the resultant is the magnitude of the resultant dynamic wind.

In making this determination, it is necessary to square the reported speeds individually, before collation by azimuth or axis, as the square of the sum of a group of numbers is not commonly equal to the sum of the squares of these same numbers. Squaring after collation is equivalent to extending the time base of the computation, so that the components may represent different time intervals, reducing the validity of the later derivations.

Resultant dynamic wind for March 1, 1944, as determined from the raw data of Table 1, is 21.6 miles (continued for one hour), from 355° (see Fig. 2D). Note the directional relations of the dominant, resultant, and resultant dynamic winds, and the lack of relation between them and the prevailing wind.

Equivalent resultant dynamic wind is the wind which, if continued steadily throughout the reporting period, has the same net work-doing ability as the reported winds.

This figure is determined from the resultant dynamic wind by retaining the azimuth unchanged, and by dividing the length of the resultant vector by the number of observations before taking the square root. This may also be found by dividing the magnitude of resultant dynamic wind by the square root of the number of observations. The equivalent resultant dynamic wind for March 1, 1944, is 4.41 mi/hr from 355°.

Comparison of average wind figures is shown in Figure 2E, where 1 is the average wind speed (or extrapolated travel), 2 the average resultant wind travel, and 3 the equivalent resultant dynamic wind.

Indicative ratios

Comparison of the observed and derived wind functions here described makes possible a number of interesting ratios, few of which, however, have any true significance. When instrumental and observational limitations are considered, only two of the many possible ratios are of general usefulness.

Directional constancy of the wind, during the period under consideration, is indicated by the ratio:

Ratio of resultant to total wind travel--The numerical value of this ratio decreases as the long-term fluctuations in direction increase. It does not give any true indication of compensating or multiple shifts of wind taking place between observations.

Long-term wind-speed constancy during the period under consideration is indicated by the ratio:

Table 5--Raw data for $22^{h}00^{m}$, March, 1944 as selected from observers' reports

Day	Direction	Speed	Day	Direction	Speed
		mi/hr			mi/hr
		Raw data			
1	WNW	6	16	SE	7
2	NNE	6	17	WNW	5
3	SE	12	18	SSE	4
4	E	3	19	NNW	20
5	E	5	20	NNW	30
6	SE	3.5	21	NE	1.5
7	SE	3.7	22	SE	10
8	SSW	1.6	23	NW	15
9	E	2.5	24	WNW	4
10	SE	3.5	25	E	2.2
11	SE	6.5	26	SW	12
12	S	4	27	ESE	2
13	ESE	2.8	28	SW	4
14	NNW	2	29	SE	2.5
15	SW	2.7	30	SSE	4
			31	N	2

Collation--Directions not reported are not listed

Direction	Reports	Total
		mi.
N	1	2
NNE	1	6
NE	1	1.5
E	4	12.7
ESE	2	4.8
SE	8	45.2
SSE	2	8
S	1	4
SSW	1	1.6
SW	3	18.7
WNW	2	11
NW	1	15
NNW	4	56

Ratio of average dynamic to average wind travel--The numerical value of this ratio increases with the gustiness.

In applying these ratios, the limitations of the instruments, observations, and statistical methods must be considered, to prevent misleading, incorrect, or absurd conclusions.

Hourly wind figures

Introduction--In many types of work, only the wind at certain hours of the day is of importance. Raw data for computation of hourly winds are obtained from observers' reports (Table 1). An example of such data, for "Oblivion Junction," for 22^h00^m, March, 1944, comprises Table 5. (The illustrative examples here used are actual records for the time, latitude, longitude, and altitude stated. The area in which these observations were made is a rather typical desert basin, having pronounced local air circulation.)

From these raw data, maximum wind (30 mi/hr from NNW) and minimum wind (1.5 mi/hr from NE) for the hour are determined by direct inspection. Average wind speed (7.82 mi/hr, the 2 being of doubtful significance) is the simple average of the reported speeds.

Hourly wind frequencies--In the collation of wind figures for 22^h00^m, March, 1944, reports are segregated by azimuths. From these data, a wind-frequency rose, similar to Figure 1, is plotted as in Figure 6B.

Hourly wind speed (or travel)--Total wind travel, by azimuths, as found by extrapolating the wind-speed reports, for 22^h00^m, March, 1944, is found by adding the collated values based on the raw data of Table 5, and is plotted in Figure 6A. When the travel along each azimuth is divided by the number of reports along the same azimuth, the average speed (or extrapolated travel) along that azimuth is obtained. This is shown in Figure 6C.

Other functions, such as resultant winds, or resultant dynamic winds, by hours, are computed in the same manner as similarly-named winds for continuous periods (previously described).

Adaptation to other reporting bases

The methods of derivation here outlined for use with the conventional 16-point reporting base are, in general, applicable with slight modification to data recorded on other bases, such as 4, 8, 12, 32, 36, and 360 points. Derivation of most functions from these bases is, in most instances, a simple, straightforward, and obvious trigonometric procedure, needing no elucidation. Prevailing and dominant winds, however, if computed on a "high-point" basis, are likely to be either misleading or meaningless. These two functions, regardless of the original reporting base, should always be reported in terms of a quadrant, octant, or half octant, the reporting sector taking its name from the source direction of the central azimuth.

Applications of data

In only a few instances is it necessary to derive an appreciable fraction of the wind functions here described. A few of the known applications of these functions will be here outlined.

In applying these derived wind data, it must be remembered that current wind reports describe only two-dimensional wind motions, completely omitting that perpendicular to the Earth's surface.

Maximum, minimum, and average wind speeds are standard data for winds, used in almost all branches of pure and applied meteorology. Maximum wind speed, as now reported by most stations, is not safely applicable to most engineering problems, as it is a true maximum only by chance. Average wind speed, usually extrapolated to become a measure of wind travel, is commonly used in computations for evaporation and ventilation.

Total wind travel, based on conventional extrapolations, is used in studies of evaporation, and as an indication of the rate of removal of local air contamination by smelter fumes. Extrapolation error here, particularly at low speeds, is frequently serious.

Prevailing direction of wind determines the locations of smelters relative to population centers, the orientation of airport runways, and similar structures. Prevailing wind does not necessarily determine the orientation of sand dunes, or the deformation of "wind timber" and cannot, in many instances, be determined from these features.

Dominant direction of wind is a crude indicator of the migration direction of wind-borne debris; and in some areas can be determined from the orientation of wind-constructed features.

"Flooring" of wind data is frequently resorted to in many types of engineering work, both to simplify the computations and to eliminate the effects of inconsequential "vagrant" breezes.

Where there are pronounced local air circulations, the axis of maximum travel determines the orientation of structures which require "natural" ventilation.

Computations of resultant wind form the basis of vastly more complicated determinations of the dissemination of smelter fumes, the distribution of pollens, the effective coverage due to crop dusting, and similar problems. The hourly wind vectors show the actual path of a "massless tumbleweed" riding the wind, and the resultant wind shows the location, with respect to the starting point, of this same "massless tumbleweed" at the end of the wind period. Classic example of this type of computation is in connection with the Trail (British Columbia) smelter-fume cases as outlined by E. W. HEWSON and R. W. LONGLEY[pp. 306-311, 1944]. Publication of a more detailed report of this study is expected shortly after the lifting of wartime regulations for security.

Ambient winds are a measure of the magnitude of purely local air circulations, and in some instances bear a definite relation to magnitude of received solar radiation in the same area (usually with a time lag).

Dynamic winds determine the amount of power available to run a windmill. As this wind, when computed from raw data measured with standard instruments, is an approximation based on the assumption that wind speed retains the same value throughout the period between observations, the computed dynamic wind may differ considerably from the actual dynamic wind.

Direction of resultant dynamic wind determines the orientation and direction of migration of sand dunes, snowdrifts, and similar aeolian features. Computations of resultant dynamic wind can be used to determine the location and orientation of drift fences and windbreaks, although a simpler and more inexpensive method "watching where the drifts form," is commonly used. In many instances, direction of resultant dynamic wind need only be determined for the drift season, and the use of data "floored" at a relatively high value is commonly justifiable.

It should be specifically noted that resultant dynamic winds, rather than prevailing winds, determine orientation and migration of aeolian structures. Hence, from study of local aeolian features, the resultant direction of dynamic wind, and not the direction of the prevailing wind, can be determined. In many areas they are similar, but in others, such as the Salt Lake Desert, the two winds are in opposition [IVES, 1946]. (Similar oppositions are noted in the San Luis Valley of Colorado, where the dunes pile up against the west face of the Sangre de Cristo Range, although the prevailing wind direction--from the east--opposes such motion. Dominant and resultant dynamic wind directions, however, favor the present dune locations.) Relation of wind behavior to dune and dust-bowl locations is briefly mentioned by VISHER [1945]; wind-dune relations are more thoroughly discussed by LANDSBERG and RILEY [1943]; and the complex interrelations of wind structure and dust transport are outlined by KEITH [1945]. Further study of these interrelations seems desirable, as the hiatus between theoretical and observed dust behavior is quite great.

Hourly wind figures are useful in determining the most opportune times for intermittent operations, and must be computed after the data needs of a specific problem are fairly well known. In some instances, when specific conditions are desired, they may be expeditiously located by inspecting the winds for various hours with relation to sunrise or sunset, rather than "clock" hours. Seasonal precessions of wind conditions are the rule, rather than the exception, in areas having strong local control.

Methods of computation

As the determination of all derived wind functions outlined above, from one year's hourly reports from one station, requires an absolute minimum of 1200 hours of skilled and diligent computation, methods employed merit careful consideration.

Primarily essential is the adoption of some rational system of determining directional designations. The raw data are somewhat "booby trapped" because of the conventional method of designating winds by their source.

Advance organization of the computations, by preparation of a sample of each type, will do much to eliminate procedural blunders. Careful checking of the computations at each stage, preferably by someone other than the original computer, tends to eliminate habitual errors, and "pyramiding" of blunders. Subdivision of the work and rotation of tasks will improve the overall accuracy.

Whenever possible, computation by machine should be used. As most of the work is simple addition, this improves the accuracy considerably, although it does not appear to shorten the computing time appreciably. Checking time, however, is shortened by use of the machine tape as a check sheet.

Constructive attention to the morale, health, and working conditions of the computing personnel is immediately repaid by a marked increase in the work output accompanied by a decline in the error rate. "Simon Legree" supervision increases the error rate faster than it does the work output.

Acknowledgments--Material herein presented is based on the experience gained during the reduction of tens of thousands of wind observations over a period of more than three years. Completion of this work was made possible by the continued diligent and faithful service of a large WAC computing squad, who, when the need arose, worked inordinately long hours, under very difficult environmental conditions, to maintain data schedules. Principal members of this squad were Sgt. (now Lt.) RITA K. WILKINSON, T/3 EVELYN L. KROONA, T/4 DOROTHY LANKIN, T/5 STELLA C. PIEKLO, and Pfc. AGNES J. MERNIN. Initial instruction of the computing squad was done by Sgt. WERNER D. SCHNACKENBURG; later instruction, and much of the "trouble shooting" by Sgt. WILKINSON. The writer is indebted to Dr. S. W. GRINNELL of Stanford University, for many helpful discussions of the nomenclature of winds and methods of computation.

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Dugway Proving Ground,
Tooele, Utah

[Note: While much of the above paper is not new, it offers an advantage in that it brings into a single summary a wide field of charting technique not heretofore available in a convenient form for reference--Ed.]

(Communicated manuscript received March 15, 1946; open for formal discussion until January 1, 1947.)

Transactions, American Geophysical Union Volume 27, Number IV August 1946

A CONTINUOUSLY RECORDING DECLINATION STATION

Fred Keller, Jr. and Albert J. Hanners

Abstract--The general lack of data on the diurnal variation and secular change of the Earth's magnetic field at other than the locations of the few magnetic observatories in the world makes it necessary to have inexpensive recording stations that may be operated unattended for long periods of time.

As partial fulfillment of this need the Coast and Geodetic Survey has proposed building a network of twenty stations in the United States. These stations are to operate for periods of three to six months without servicing, and are eventually expected to continuously record the three magnetic elements: declination, horizontal intensity, and vertical intensity.

The Gatlinburg Declination Station

The first experimental station has been constructed by the United States Coast and Geodetic Survey in cooperation with the National Park Service in the Great Smoky Mountains National Park at Gatlinburg, Tennessee. Declination is the only element recorded at present; however, it is expected that the other elements will be added in the future. This station was operated from October 1945 to February 1946, at which time it was serviced and allowed to operate until April 1946. The experimental records are so promising that the equipment has been returned to Washington to serve as a model for the construction of instruments for similar stations elsewhere.

The variation building--The instruments are housed in a small wooden building which rests on a concrete foundation (Fig. 1). The exterior is covered with clapboards stained with creosote. Underneath the clapboards there is a layer of building felt and storm sheathing. The outer door opens into a small light-trap where a voltage-supply panel, batteries, and synchronous clock are mounted. In the main part of the building there is a concrete pier which is eight feet long, two feet wide, and about thirty inches high for the variometer and recorder. The long axis of this pier is oriented east-west, and the magnetic prime vertical is marked on the top. A shelf for developing trays and chemicals is fastened to the south wall of the main room.

Absolute station--The value of the base line for the D-variometer is determined at an absolute station 123 feet east of the variation building. This point is marked in the same manner as magnetic repeat stations. There is a concrete post bearing a standard bronze disk and three concrete tripod posts at the point where the absolute observations are made. Monuments are located to the northeast and to the east about 250 feet from the absolute station for azimuth marks.

At the times when the station is serviced, an observer makes eight sets of declination observations with a standard field magnetometer at the absolute station. The time is indicated on the recorder tape by turning the recorder lamp off for fifteen minutes before and after each set. Four sets of declination are made before removing the record from the camera and four sets after the beginning of the new record.

This is essentially the same procedure used for determining the values of base lines at magnetic observatories. The base lines at Gatlinburg remained reasonably constant during the experimental period, despite the fact that some of the observations were made during periods of magnetic storms.

Recorder--A satisfactory recorder was obtained by modifying an obsolete model of the Sanborn electrocardiograph camera (Fig. 2). The record is made on bromide paper, which has a perforated width of six cm. The paper is drawn past a slit, at a rate of two mm per hour, with a sprocket, and is rolled on a "take-up" spool in the bottom of the recorder. Since there are 75 feet of paper on a spool, there is enough to make a continuous record for 14 months without servicing.

The lamp for the base line and trace spots as well as the cylindrical lens and diaphragm are contained in the body of the camera. The spots are flashed on the bromide paper once every five minutes by a circular shutter, which has two sectors cut from it and which revolves once every ten

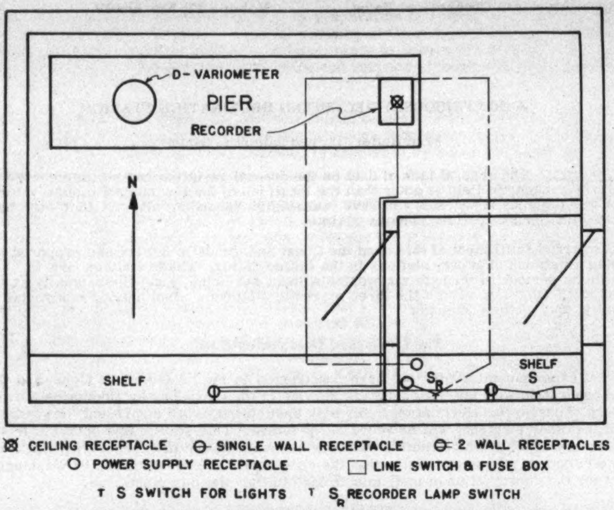

Fig. 1--Wiring diagram and floor plan, declination station, Gatlinburg, Tennessee

minutes in front of the lamp window. The sectors are so proportioned that the duration of the recording spots is about 30 seconds. It is necessary to have this shutter because the spots continuously recording at a paper-speed of two mm per hour would fog the record.

A time break is recorded every twenty-four hours by having the light turned off with a cam-operated microswitch for twenty to twenty-five minutes. This makes a break in the record of four or five spots, and in operation the time-marking cam is set so that the first spot after the break records at midnight.

The sprocket, take-up spool, shutter, and time-marking switch are driven by gear trains which are coupled to a Holtzer-Cabot 110-volt synchronous motor. The torque supplied by the one-rpm shaft of this motor is 75 inch-ounces. There are six-volt direct-current constant-speed motors available which have approximately the same power output, and which make it possible to have a battery-operated recorder. In areas where 110-volt alternating current is not available, wind chargers could be used to keep the batteries charged.

Voltage supply--A voltage-supply panel (Fig. 3) which automatically switches the recorder onto storage cells in case of failure in the 110-volt source was installed in the Gatlinburg Station. The charge is maintained in the storage cells with a trickle charger which operates while the 110-volt power is on. The storage cells operate a 12-volt converter which supplies 110-volt, 60-cycle alternating current to the camera motor and lamp transformer. Resistances in the 110-volt and 12-volt circuits are made slightly different so the recorder lamp has 300 milliamperes supplied to it when the normal power is on, and 320 milliamperes when the storage cells are on. This varies the intensities of the spots and makes it possible to determine if and when the power has been off. Fluctuations in line voltage may result in losing parts of the traces, so a voltage regulator is placed in the 110-volt input circuit. A synchronous clock is wired in parallel with the voltage supply and the recorder. This clock is set to exact time, and the time-marking cam is synchronized with it to make the first spot recorded after the time break occur at midnight.

Variometer--The variometer which was used for this experimental work is a Schultze D-variometer which was modified by the Coast and Geodetic Survey in 1944. This instrument consists of a small (two mm × 10 mm) Alnico II magnet suspended from a torsion head with a silica

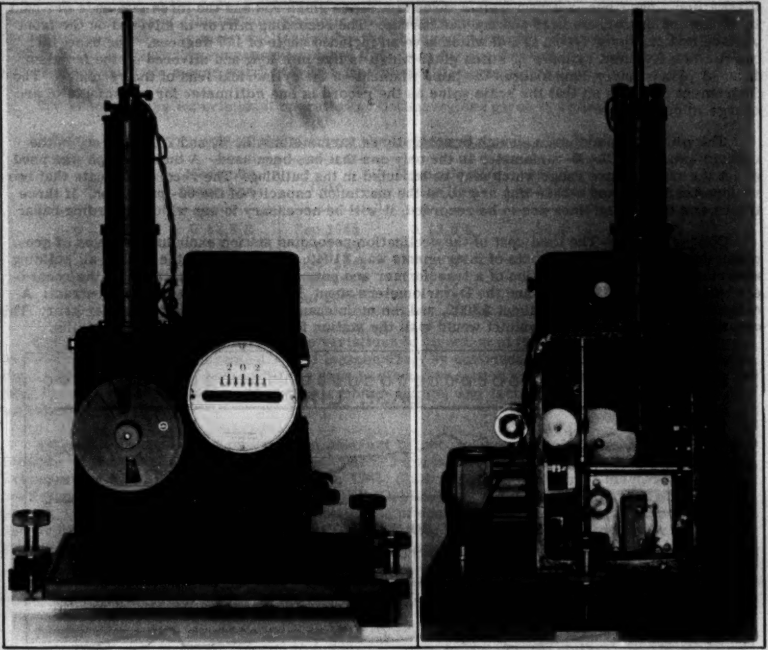

Fig. 2--Front and side views, 60-mm tape recorder (overall height recorder about 46 cm)

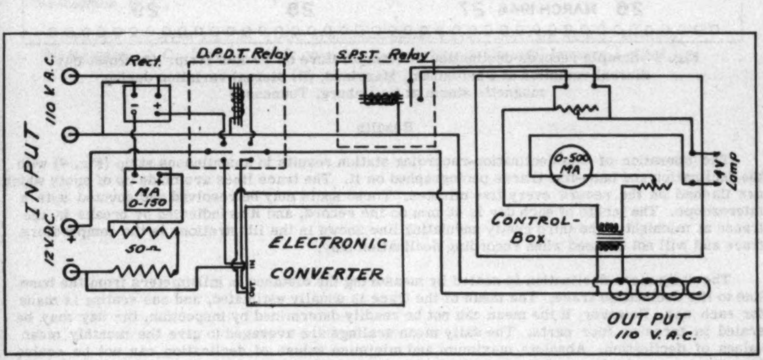
INPUT
110 V.A.C.
12 V.D.C.
+
-
Rect.
D.P.D.T. Relay
S.P.S.T. Relay
MA 0-150
50-Ω
ELECTRONIC CONVERTER
CONTROL-BOX
0-500 MA
4V Lamp
OUTPUT
110 V.A.C.

Fig. 3--Power-supply diagram for declination recording station glass fiber. The fiber is drawn from a three mm silica glass rod and the three mm ends are held by chucks on the torsion head and magnet stirrup. The recording mirror is silvered on the front surface and has three faces, two of which have an included angle of 177 degrees. The base-line mirror is a five-mm cylinder of silica glass which is five mm long and silvered on the front surface. A plano-convex lens focuses the lamp filament on the cylindrical lens of the recorder. The instrument is set up so that the scale value on the record is one millimeter for one minute of arc change in declination.

The pier was made large enough to set up three variometers (D, H, and Z); however, in the experimental work the D-variometer is the only one that has been used. A thermograph was used to get the temperature range which may be expected in the building. The records indicate that two variometer traces and a base line are about the maximum capacity of the 60-mm paper. If three traces and three base lines are to be recorded, it will be necessary to use wider recording paper.

Cost of Station--The total cost of the declination recording station excluding salaries of geophysicists and development costs of instruments was $1040. This included the cost of all building materials, labor, and installation of a transformer and power line. It is expected that the recorders will cost about $700 each and the D-variometers about $1500 each when built on contract. A complete station should total about $3000, and the maintenance should be about $500 per year. This estimate implies that a geophysicist would visit the station for three days every four months.

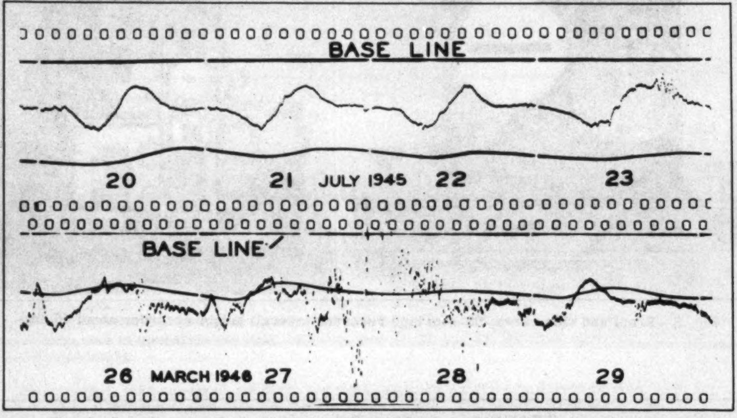

Fig. 4--Sample records declination and temperature on 60-mm strip: (A) Quiet-day diurnal variation at Cheltenham, Maryland; (B) diurnal variation during magnetic storm at Gatlinburg, Tennessee

Results

The operation of this declination-recording station results in a continuous strip (Fig. 4) with the declination and base-line traces photographed on it. The trace lines are made up of spots which are flashed on the record every five minutes. These spots may be resolved and counted with a microscope. The length of each day is 48 mm on the record, and it is indicated by breaks in the traces at midnight. The third gently undulating line shown in the illustrations is the temperature trace and will not be used when recording declination only.

The daily mean declination is scaled by measuring the distance in millimeters from the base line to the declination trace. The mean of the trace is usually estimated, and one scaling is made for each day. However, if the mean can not be readily determined by inspection, the day may be scaled in three or four parts. The daily mean scalings are averaged to give the monthly mean values of declination. Absolute maximum and minimum values of declination can not be scaled from these records, because the traces are only recorded for 30 seconds every five minutes. This is not considered to be a serious drawback, because it is the daily and monthly means of magnetically quiet days that furnish the most useful data.

A comparison of the results obtained from the Gatlinburg instruments and the Eschenhagen No. 5 magnetograph at Cheltenham Magnetic Observatory was made for a 26-day period during the summer of 1945. The mean declination for the 26 days determined by scaling daily means was 7°05.′7 W for the Gatlinburg magnetograph and 7°05.′4 W for the Eschenhagen No. 5. The average difference of the daily means was 0.′4 with a maximum difference of 0.′8.

The results of the experimental operation at Gatlinburg are given in Table 1.

Table 1--Base-line values at Gatlinburg Continuously-Recording Declination Station

Date	Mean obs. base line	Date	Mean adopted base line	Mean ordinate	Mean D (scaled)
	° ′		° ′	′	° ′
Sep 2, 1945	0 13.5 E	Sep 1945	0 13.8 E	20.4	0 34.2 E
Sep 18, 1945	14.0	Oct 1945	13.8	20.8	34.6
Sep 18, 1945	13.8	Nov 1945	13.8	21.2	35.0
Feb 1, 1945	13.8	Dec 1945	13.8	21.1	34.9
		Jan 1946	13.8	21.2	35.0

Conclusions--It is concluded that the variations in direction of the Earth's magnetic field may be recorded accurately, conveniently, and inexpensively by continuously-recording declination stations. These stations will help to fill the gaps in diurnal variation and secular-change data that now exist because of the sparseness of magnetic observatories and lack of homogeneity in field observations.

Acknowledgments--This paper is an abstract of several reports of chiefs of party to the Director of the Coast and Geodetic Survey. These reports are: (1) Declination Station, Gatlinburg, Tennessee by ALBERT J. HANNERS, July 14, 1945; (2) Report on experimental magnetograph for the Temporary D-Station in Tennessee by FRED KELLER, Jr. and C. EDWARD WESTERMAN, July 10, 1945; and (3) Directions for the installation of declination observatory at Gatlinburg, Tennessee by R. E. GEBHARDT and H. E. McCOMB, July 28, 1945. These are unpublished reports in the files of the Division of Geomagnetism and Seismology of the Coast and Geodetic Survey.

The modifications of the Sanborn electrocardiograph camera were made in the instrument shop of the Coast and Geodetic Survey by the late DAVID WARK.

Special recognition should be given to officials of the National Park Service at the Great Smoky Mountains National Park for cooperation and assistance in building the station. BLAIR ROSS and ROBERT CRESWELL were especially friendly and helpful.

U. S. Coast and Geodetic Survey,
Washington, D. C.

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Transactions, American Geophysical Union Volume 27, Number IV August 1946

SEISMIC SEA WAVE OF APRIL 1, 1946, AS RECORDED ON TIDE GAGES

C. K. Green

Abstract--Records from some 20 tide stations in the eastern Pacific Ocean, covering a stretch from 57°N latitute to 33°S latitude, which show the onset of the seismic sea wave of April 1, 1946, are analyzed. Travel-time curves, computed from the formula $V = \sqrt{gd}$, are shown to be in good agreement with the observed times of arrival of the seismic sea wave. The average ratio of initial rise to succeeding fall of the water is found to be one to three, which may account for the frequent mention of an initial recession by eyewitnesses. The first half period is derived as a measure of the period of the seismic sea wave which is found to average 15.6 minutes. The period for the nearer stations averages 15.0 minutes, while for the farther stations it averages 17.4 minutes.

The seismic sea wave of April 1, 1946, was recorded at 15 United States Coast and Geodetic Survey tide stations on the Pacific coast and at Honolulu. It was also recorded at two cooperative stations in Chile, two in Peru, and one in Costa Rica. Through the courtesy of the Canadian Hydrographic Service, records from several places on the west coast of that country are available. These 20-odd stations range from 1000 to 8000 statute miles from the epicenter of the earthquake, the location of which is in depths of 2000 fathoms some 80 miles southeast of Unimak Island, Alaska, on the steep slopes of the Aleutian Trench.

More data for the oceanographer are contained in these records than have heretofore been available for a wave originating in this area. Before examining the tide records, it may be well to consider velocities.

Computed half hourly travel-time curves shown in Figure 1 are based on the simple velocity formula for long waves, $V = \sqrt{gd}$, using depths given on Chart 9000 of the Northeast Pacific. The black dots along the coast show the locations of tide gages which recorded the wave in this part of the ocean. Open circles indicate where gages were in operation at places not visited by the wave.

Since the speed of the wave increases with depth, the probable path is, of course, not always the single great circle from the epicenter. Thus travel time was computed, for each 60-mile section, over branches and sub-branches of great circles until a sufficient number of values were determined to draw the curves as you see them here in the Northeast Pacific. By the curves it can be seen that the travel time is about the same--4-1/2 hours--to the Hawaiian Islands, Washington, Oregon, and northern California. Also the curves show the retarding effect of the shoaler areas of the Gulf of Alaska.

The greatest velocity that the wave could have attained en route to the Hawaiian Islands is 600 statute miles per hour while crossing the 4000-fathom depths of the Aleutian Trench. Actually, the average velocity of the wave to Honolulu was 490 statute miles per hour. The computed travel time to Valparaiso, Chile, is 18 hours and 37 minutes. Actually, the wave found a better route than we did and arrived there 30 minutes ahead of schedule.

Velocity data are shown in Table 1. The computed values in the fourth column of figures are based on the best early determination of the epicenter. Later, when additional earthquake data became available, the epicenter was computed to be about 45 miles southeast of the preliminary determination. The last column shows the computed travel time minus observed travel time based on the latest fixing of the epicenter by the seismologists.

This paper was first written on the basis of the preliminary location of the epicenter, and the following comment was then made, "It is interesting to note that in all cases the computed time of arrival is greater than the observed. Whether this is significant or not we do not know, since the differences are small, and we do not know precisely the depths in many places of the ocean. Moreover, gage clocks are not chronometers and differences of a minute or so from exact times are possible on the records."

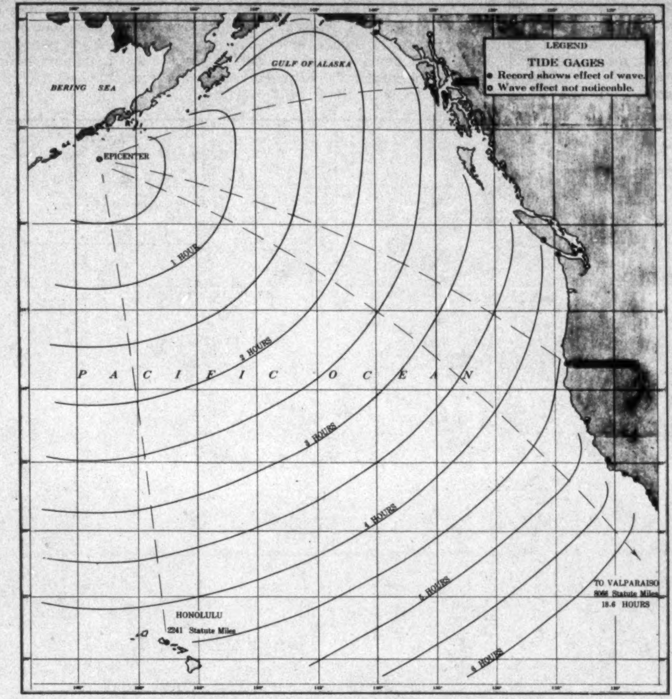
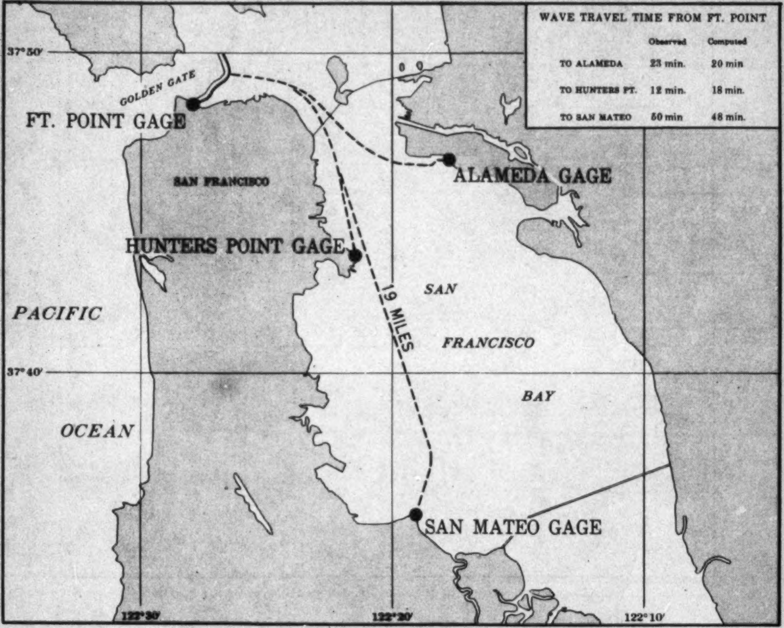

BERING SEA
GULF OF ALASKA
EPICENTER
LEGEND
TIDE GAGES
● Record shows effect of wave.
○ Wave effect not noticeable.
1 HOUR
2 HOURS
3 HOURS
4 HOURS
5 HOURS
6 HOURS
PACIFIC OCEAN
HONOLULU
2241 Statute Miles
TO VALPARAISO
8066 Statute Miles
18.6 HOURS

Fig. 1--Travel-time curves, seismic sea wave of April 1, 1946

Table 1--Wave travel time, seismic sea wave of April 1, 1946

Station	Distance from epicenter	Mean observed velocity	Observed travel time	Time difference (computed minus observed) epicenter at	
				54°N, 164°W	53-1/2°N, 163°W
	stat mi	stat mi/hr	h m	min	min
Honolulu	2241	490	4 34	+ 3	- 4
Clayoquot	1610	374	4 18	+ 9	- 1
Neah Bay	1687	373	4 31	+ 10	0
Crescent City	1950	421	4 38	+ 16	+ 6
San Francisco	2197	398	5 31	+ 16	+ 6
San Luis Obispo Bay	2392	427	5 36	+ 8	- 2
Port Hueneme	2504	424	5 54	+ 11	+ 1
La Jolla	2646	428	6 11	+ 18	+ 8
Talara	6134	422	14 31	+ 12	+ 2
Matarani	7193	438	16 26	+ 33	+ 23
Antofagasta	7622	439	17 21	+ 7	- 3
Valparaiso	8066	445	18 07	+ 40	+ 30
Mean percentage variation (computed over observed)				3.2 per cent	1.2 per cent

Apparently it was significant, for we now have, in the last column, the scattering of both plus and minus differences which is to be expected if everything is shipshape. The mean percentage of difference as seen at the bottom of the Table seems remarkably small. The greatest percentage difference for a single station is 2.8 per cent. It might be well to remark that travel times to the South American stations were computed before the observed times were available--in fact, before it was known that the wave was recorded at the stations.



WAVE TRAVEL TIME FROM FT. POINT

	Observed	Computed
TO ALAMEDA	23 min.	20 min
TO HUNTERS PT.	12 min.	18 min.
TO SAN MATEO	50 min	48 min.

Fig. 2--Wave travel time to gages inside San Francisco Bay

Computed and observed velocities of the long wave in shoal water can be compared in San Francisco Bay, where four gages recorded the wave. Figure 2 shows the probable path and the travel time to gages inside the Bay, using the time of passage of the wave front at the gage in Golden Gate as the initial. Travel time from Golden Gate to San Mateo, a distance of 19 miles, was computed to be 48 minutes, while actually the wave reached San Mateo in 50 minutes. Also, in the case of Alameda the computed travel time checked reasonably well with the observed time. At Hunters Point a good check was not obtained because the observed time of arrival is somewhat uncertain. In the south arm of the Bay, the wave had a speed of about 20 miles per hour to San Mateo.

In a sense, we have "trapped" a wave between Golden Gate and Alameda. The records show that 1.4 waves passed the Fort Point station before the first wave front reached the Alameda Station. With a distance of nine miles, the wave length would be about six miles in the comparatively shoal waters of the Bay.

Figure 3 is a tide marigram on which is shown a height scale in feet along the left edge and a time scale in hours along the bottom. The height scale is not referred to any special datum. The figure shows the tide curve at Honolulu for ten hours on the day of the seismic wave. Long and short period oscillations of small amplitude, common to Honolulu Harbor, are seen superimposed on the rising and falling tide until the arrival of the wave at about 17^h Universal Time (GCT). At

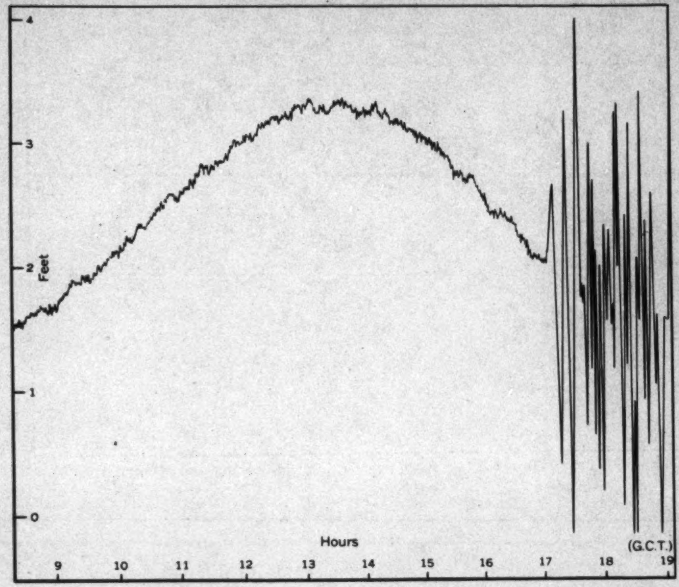


Fig. 3--Tide gage record at Honolulu, Hawaii following earthquake of April 1, 1946

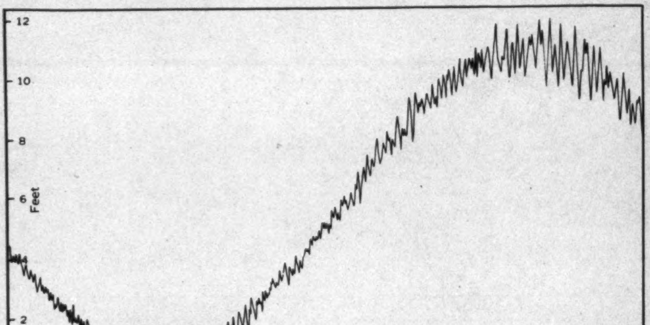


Fig. 4--Tide gage record at Yakutat, Alaska following earthquake of April 1, 1946

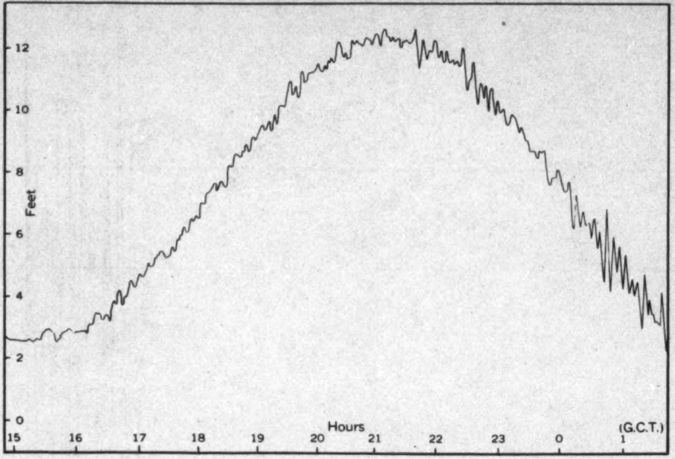


Fig. 5--Tide gage record at Sitka, Alaska following earthquake of April 1, 1946

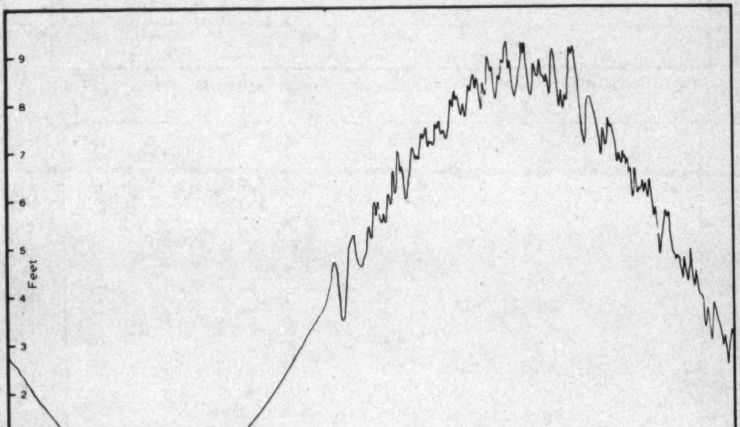


Fig. 6--Tide gage record at Clayoquot, British Columbia following earthquake of April 1, 1946

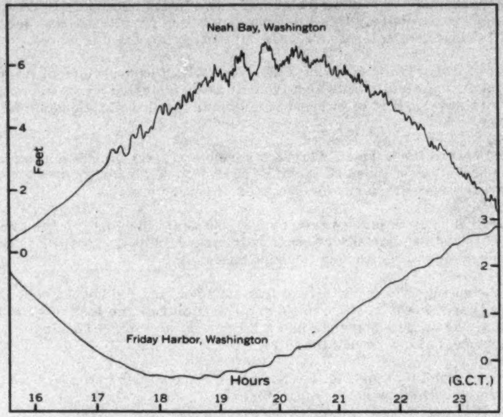


Fig. 7--Tide gage records at Neah Bay, Washington and Friday Harbor, Washington following earthquake of April 1, 1946

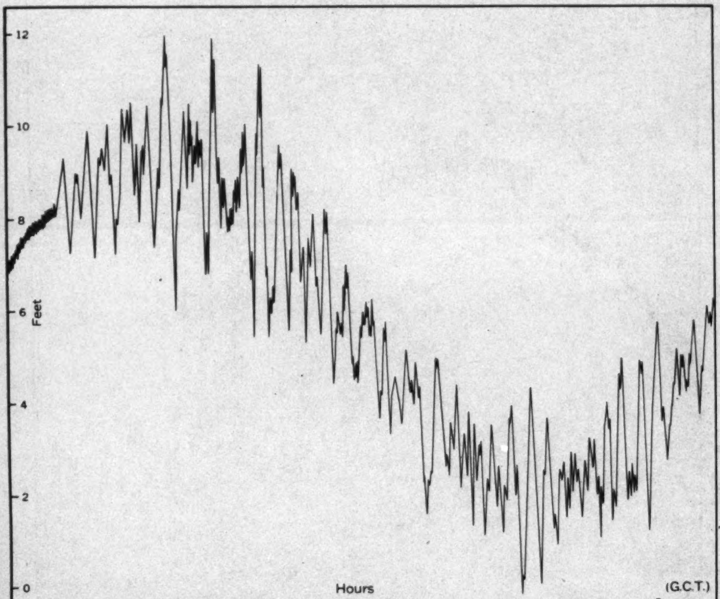


Fig. 8--Tide gage record at Crescent City, California following earthquake of April 1, 1946

Honolulu the disturbance started with a rise of half a foot in six minutes, followed by a fall of two feet in seven and one-half minutes. This is a general pattern for all stations--the average ratio of initial rise to fall is about one to three, after the effects of tide are eliminated.

In HECK'S list of 200 seismic sea waves [HECK, 1934] of past centuries, two points stand out. Eyewitness reports generally state that the disturbance started with a recession and state that there were three waves. It is of interest to keep this in mind while examining the records of this particular wave.

Figure 4 is the record for Yakutat, Alaska, where the arrival time is not definite because of the existing seiche action present before the wave arrived, and also because the wave had lost much of its energy in passing over considerable distances of shoal water.

The time of arrival at Sitka is seen (see Fig. 5), but again the energy of the wave is largely spent. A number of islands and extensive shoal waters lie off Sitka. Figure 6 is the record for Clayoquot on the ocean side of Vancouver Island, Canada.

Neah Bay, at the entrance to the Straits of Juan de Fuca, and Friday Harbor, nearly a hundred miles inside the Bay, are shown together in Figure 7 to illustrate the loss of wave height in passing from a comparatively narrow entrance into a large body of water. The Seattle gage, some 125 miles from the entrance, did not record the wave.

The curve at Crescent City (see Fig. 8) shows well the complex pattern of oscillations brought about by the wave, but modified by local seiche periods.

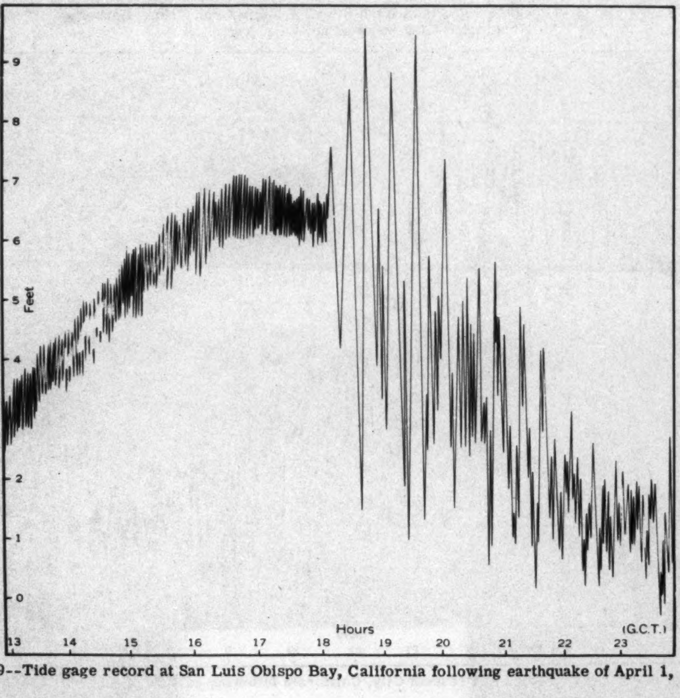


Fig. 9--Tide gage record at San Luis Obispo Bay, California following earthquake of April 1, 1946

At San Luis Obispo (see Fig. 9) the gage recorded a maximum range of eight and one-half feet. The oscillations occurring before the arrival of the seismic wave have a period of about four minutes and a height of one foot. They are, of course, of local character.

A local 12-1/2 minute period seiche is usually present on the records at Hueneme, as shown in Figure 10. The uniformity of oscillations set up by the seismic wave indicates that the seismic wave period is close to either the fundamental or a harmonic of the local period. The Hueneme station is located at the head of a deep submarine canyon.

Figure 11 is the record for La Jolla, where the initial oscillation is of the orthodox pattern, but where local effect is present soon after the wave's arrival.

Valparaiso, 8066 statute miles from the epicenter, is the most distant station for which we presently have a record of the wave (see Fig. 12). Here, as at the other stations, the initial rise was only one-third the amount of the following fall. It seems possible that at many places the disturbance would not be obvious to those present until the sea recedes rapidly and surge starts. Therefore, it appears that eyewitness reports of recession first should be accepted with caution when considering the characteristics of this long wave.

In attempting to derive the period of this particular wave, it was found that soon after the wave arrived the local seiche became active, and a complex pattern of oscillations resulted. Therefore, the first measurable half-wave period seemed to be a reasonable basis for deriving the true period.

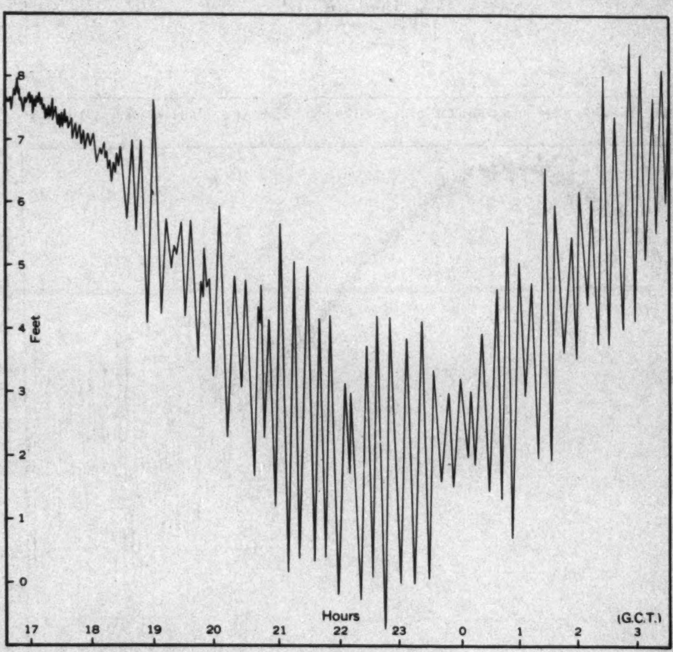


Fig. 10--Tide gage record at Port Hueneme, California following earthquake of April 1, 1946

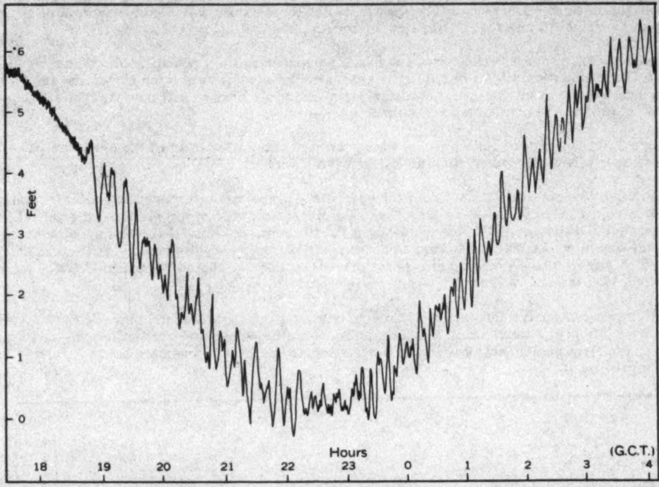


Fig. 11--Tide gage record at La Jolla, California following earthquake of April 1, 1946

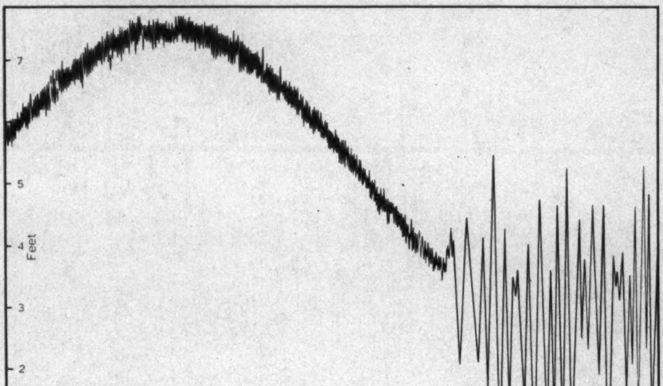


Fig. 12--Tide gage record at Valparaiso, Chile following earthquake of April 1, 1946

Table 2--Wave period, seismic sea wave of April 1, 1946

Station	Time interval, first crest to first trough
	min
Honolulu, T. H.	7-1/2
Clayoquot, Canada	8
Crescent City, California	7
San Luis Obispo Bay, California	8
Port Hueneme, California	7-1/2
La Jolla, California	7-1/2
Talara, Peru	8
Matarani, Peru	8
Valparaiso, Chile	9
Mean (half-wave period)	7.8
Wave period	15.6

Shown in Table 2 are nine stations selected as more nearly representing open ocean conditions. At these stations the time in minutes from the initial crest to trough was scaled from the records. The mean of these values gives a half-wave period of 7.8 minutes, making the full-wave period 15.6 minutes.

The waters of San Francisco Bay were quite undisturbed by local seiche when the wave arrived. By taking the mean of the first two oscillations at the four stations in the Bay, a period of 15.1 minutes is obtained.

Thus the preliminary determination of the mean period of this specific seismic sea wave is to the order of 15 or 16 minutes. This period gives a wave length of 100 to 150 miles in the deeper areas of the ocean.

When the curves from widely separated stations are examined, differences in the wave period are noted. Although the limitations of scale and the mechanics of gage operation must be kept in mind, the geographic variations in scaled half-wave values appear, nevertheless, to have significance.

Half-wave periods at the four outside stations in California and the four in Peru and Chile can be compared in Table 3.

Table 3--Comparison of half-wave periods

Station	Distance from epicenter	Half-wave period first crest to first trough
	stat mi	min
Crescent City, California	1950	7
San Luis Obispo, California	2392	8
Hueneme, California	2504	7-1/2
La Jolla, California	2646	7-1/2
Mean	2373	7.5
Talara, Peru	6134	8
Matarani, Peru	7193	8
Antofagasta, Chile	7622	10
Valparaiso, Chile	8066	9
Mean	7254	8.7

Thus the records for this seismic sea wave indicate an increase in period of about two minutes (from 15 minutes to 17 minutes) in a distance of 5000 miles.

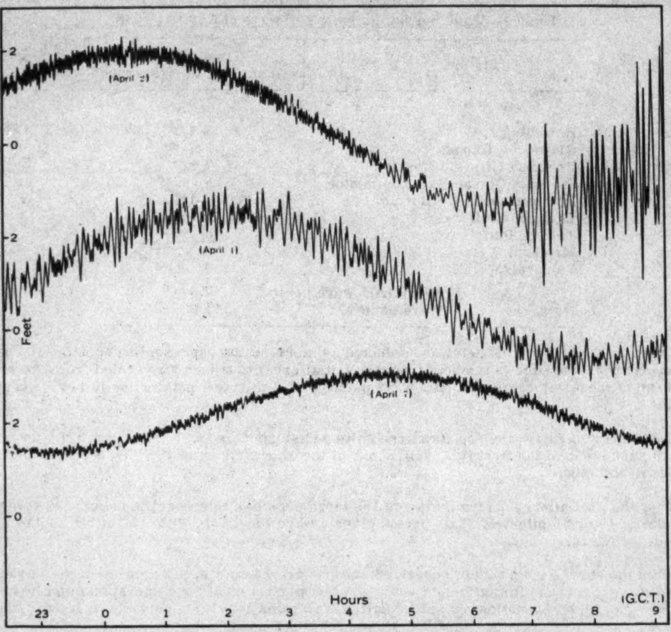


Fig. 13--Tide gage record at Matarani, Peru following earthquake of April 1, 1946

The time of the wave's arrival at Matarani, Peru, appears indefinite at first glance (see Fig. 13). By looking for the first half-wave period of about eight minutes, the arrival time is found to be some two hours before the beginning of the larger oscillations. This time is in close agreement with the computed time over the great circle route, which passes east of the Galapagos Islands. This happens to be the fastest of several routes, but it also passes over areas of less depth, and the wave, therefore, first reached the station with somewhat diminished energy, and we see first only minor effects.

The upper tide curve is for eleven hours on April 2, 1946, the second curve is for the same hours on April 4, with the seismic wave still in evidence. The last curve is on April 7, when the water had returned to normal.

Reference

HECK, N. H., List of seismic sea waves, Ann. Comm. pour l'Etude des Raz de Maree, no. 4, pp. 20-41, 1934.

[See also Papers in Seismology in this issue for a paper by RALPH R. BODLE, entitled "Note on the Earthquake and Seismic Sea Wave of April 1, 1946--Ed]

U. S. Coast and Geodetic Survey,
Washington, D. C.

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JAPANESE OCEANOGRAPHIC AND MARINE BIOLOGICAL STATIONS

Charles J. Fish

On a recent mission to Japan for the United States Navy, the author was afforded an opportunity to interview representatives of the oceanographic and marine biological laboratories of the home islands, Korea and Formosa. In all, 83 members of 41 oceanographic institutions and university departments concerned with various aspects of oceanography were interviewed.

To facilitate comparison of the prewar and present status of the institutions, the following resumé has been prepared in the same form as that in the catalogue published by the National Academy of Sciences [VAUGHAN, 1937]. The item on income, however, has in most instances been omitted, since future financial support cannot be predicted at this time.

With the exception of the Palao Tropical Biological Station, which was completely destroyed by aircraft bombing in 1944, all prewar Japanese oceanographic institutions and those established during the War are either in operation or are planning to resume operations in the near future.

Acknowledgment is made to JOHN CATT, Lieut. RNVR, interpreter and translator, and to TUSHIO AKIYOSHI, former Rear Admiral, IJN, technical assistant and translator, for valuable assistance in the acquisition and assembling of documents and data.

Geographical Distribution

(a) Tokyo Area

- Hydrographic Department
- General Central Meteorological Observatory of Japan
- Imperial Fisheries Experimental Station
- Imperial Fisheries Institute
- Misaki Marine Biological Station
- Kominato Marine Biological Laboratory

(b) North of Tokyo

- Onagawa Fisheries and Oceano-Chemical Laboratory
- Miyako Meteorological Observatory
- Hachi no-he Meteorological Observatory
- Asamushi Marine Biological Station
- Hakodate Marine Observatory
- Oceanographic Division, Institute of Low Temperature Science
- Akkeshi Marine Biological Station
- Oshoro Marine Biological Station
- Institute of Algological Research

(c) West of Tokyo

- Shimoda Marine Biological Station
- Mitsui Institute of Marine Biology
- Sugashima Marine Biological Station
- Imperial Marine Observatory, Kobe
- Institute of Physical Oceanography
- Seto Marine Biological Laboratory
- Onomichi Marine Biological Laboratory
- Amakusa Marine Biological Laboratory

(d) Korea

- Fisheries Research Station, Chosen

(e) Formosa

Formosan Government Marine Fisheries Experiment Station

(f) Palao Islands

Palao Tropical Biological Station

The above list does not include prefectural fisheries experimental stations, commercial fisheries laboratories, and personal laboratories of marine zoologists.

(a) Tokyo Area

Hydrographic Department

History or origin--Established 28 July 1871, first under the War Department as the Naval Hydrographic Bureau, transferred in 1872 to the Navy Department, which was established during that year. The Naval Meteorological (Third) Division became an independent department in 1944.

Location--5 Chome, Tsukizi, Hyobashi Ward, Tokyo.

Organization to which attached--Ministry of Transportation since 28 November 1945.

Purposes--Under the Imperial Japanese Navy the Hydrographic Department conducted the preparation and issue of hydrographic and aeronautical publications, undertook the survey of coasts and seas, made recommendations and issued notices regarding safety of navigation, and trained hydrographic engineers. It also conducted surveys, observations, and research on meteorology and oceanography for the Navy.

Organization--The organization of the Hydrographic Department was revised in May 1941, and again in November 1945, when the Department was transferred from the Ministry of the Navy to the Ministry of Transportation. The present organization is as follows: Secretariat - Executive and Accounts Sections; First Division - Surveying, Oceanography, and Astronomy Sections; Second Division - Compilation and Printing Sections and Hydrographers Training School.

Branches--There are no branch offices, but during the War the Hydrographic Department supplied technical material, personnel, and apparatus to equip two hydrographic field stations and a third field station for general research established to serve under the Fleet Command and be responsible only to the Command, as follows:

(1) The Shanghai Hydrographic Office was established to serve the China District Fleet. Its activities were confined to the Yangzte River and its approaches. Y. HOURI was the first Director, and Captain Y. IMAMURA the last. Work terminated when the War ended.

(2) The Southern Hydrographic Office was established in June 1943, to serve the Southwest District Fleet, and was located at Surabaya. T. ARUGA was the first Director, and Y. HOURI the second and last. The office closed in February 1945. Extensive oceanographic survey work was carried out in the region under Captain N. DAITO, and the results were published as confidential serials of the Southern Area Navy Route Department. (Officials reported that all documents received in Tokyo from the Southern Hydrographic Office had been destroyed.)

(3) A third field station, the Makassar Research Station, was established under Japanese Navy Administration in Makassar in 1943 (?). This was not a marine station. It was developed for comprehensive terrestrial investigations. Seven sections were planned: Administration, medicine, hygiene, geology, forestry, agriculture, and habits and manners of natives. Little word was received in Tokyo from this Station. According to Rear Admiral AKIYOSHI, Dr. S. HATAI joined the staff after leaving Palao and was probably the Director. Only the Department of Political Affairs for the Southern District (Nanpo-Seimu-Bu) of the Ministry of the Navy maintained contact with the Station. The Hydrographic Department could obtain no information; Admiral AKIYOSHI was later informed that little if any research had been carried out.

Equipment--Prior to the War the Hydrographic Office had acquired six surveying vessels (1400-4000 tons) and six oceanographic observation vessels (200 tons). Most of these were either

sunk during the War or otherwise disposed of. At the present time three remain available for service, namely, Kaiyo-Maru No. 3 (200 tons), Kaiyo-Maru No. 4 (200 tons), and Tenkai-Maru (120 tons). An earthquake in 1923 destroyed most of the buildings. The Institution was rebuilt by 1933 and thereafter expanded by the addition of a storehouse in 1938, operating rooms for oceanographic and meteorological work in 1940, and for aerial-photo surveying in 1942. In an air-raid on 10 March 1945, the greater part of the Institution was burned, leaving intact only the main building, a foundry, and three storehouses.

Provision for publication of results--Notices to Mariners, Translation of Foreign Sailing Directions, Sailing Directions for Japan, The Russian Maritime Provinces, The China Pilot, Sailing Directions for Bengal, Philippine Islands, Borneo, the western and eastern sides of the China Sea, and most parts of Eastern Archipelago and Hawaii, 55 volumes; Ocean Passages, one volume; Coastal Passages, one volume; the Light Lists for Japan and other parts of the Orient, two volumes; separate volumes of sailing directions, various maritime regulations, Tide-tables, Nautical Almanac, Astronomical Navigation Tables, Distance Tables, List of Japanese Place Names, tidal and current charts, Hydrographic Bulletin (Suiro-Yoho), Bulletin of the Hydrographic Department, and oceanographic text books.

Postwar status--When the War ended, certain permanent staff members occupying key positions in the Hydrographic Department were replaced by high-ranking Naval Officers of the Line seeking secure jobs. Rear Admiral T. AKIYOSHI, who had served in the Department for many years and throughout the War had been in charge of the former Second Division (surveying, oceanography, astronomy), was one of the permanent staff members displaced in September 1945. In accordance with a directive by SCAP (Supreme Commander Allied Powers), these new officers were later forced to resign, leaving the Department badly disorganized.

Another directive by SCAP (SCAPIN-794), dated 5 March 1946 (CE), ordered "immediate resumption of normal peacetime functions of Japanese Hydrographic Department." The directive in effect authorized the resumption of hydrographic and oceanographic work essential to shipping and the fishery industry in Japanese home waters. The Director of the Ministry of Transportation is Acting Director of the Hydrographic Department (9 March 1946), pending selection of a Director.

General Central Meteorological Observatory of Japan

History or origin--Established in 1876.

Location--Takehira-tyo-2 and Otemachi-1, Kojimachiku, Tokyo.

Organization to which attached--Ministry of Transportation (transferred from Ministry of Education in 1943).

Purposes--General meteorological investigations, including allied researches in oceanography, seismology, weather forecasting and warning, and terrestrial magnetism.

Scope of activities--(1) Weather forecasting and warning and printing weather charts, (2) radio reception and sending of weather reports, (3) workshops for construction of instruments, (4) chronometer repairing, (5) solar radiation and its influence on living organisms, (6) oceanographical investigations, (7) seismology, (8) terrestrial magnetic observations, (9) chemical meteorology, (10) agricultural meteorology, (11) sanitary meteorology, and (12) aerology.

Equipment--(1) General business offices, (2) meteorological laboratories, (3) weather service equipment, and (4) workshops for repair and manufacture of instruments.

Branch observatories--(1) Imperial Marine Observatory, Kobe, (2) Miyako Meteorological Observatory, (3) Hakodate Marine Observatory, (4) Hachi no-he Meteorological Observatory.

Vessels (Tokyo)--(1) M. S. Ryohu-Maru, steel vessel of 1200 tons, special construction for meteorological and oceanographical observations, length 225 ft, beam 35 ft, twin screws, speed 15 knots; (2) M. S. Asashio-Maru, 58 tons, length 21.9 meters, breadth 4.9 meters, speed 8.5 knots; (3) M. S. Yushio-Maru, 140 tons, length 29.6 meters.

Staff--1813 total; 70 engaged in special investigations; Director, Dr. S. FUJIWHARA; Chief of the Forecast Division, Dr. K. WADACHI; Chief of the Research Division, Dr. K. HIDAKA; Chief of the Investigation Division, Dr. H. ARAKAWA; in charge of Oceanography Section, Dr. K. HIDAKA; Oceanographer, Dr. Y. TAKENOUTI; Oceanographer and Limnologist, Dr. S. YOSHIMURA; Chief

Chemist, Dr. Y. MIYAKE; Biologist, Dr. S. WADA; Physical Oceanographer, Mr. N. WATANABE; Oceanographer and Meteorologist, Mr. M. HARAGUCHI; Vessel Captain, Mr. K. NAKANO; Marine Engineer, Mr. H. KOSUGE.

Provision for publication of results--Monthly and annual reports of Meteorological Observations in Japan; Monthly Weather Review; Geophysical Magazine; Bulletin; Actinometric Bulletin; Solar Radiation; Tide-tables; Short Report of results of observations on solar radiation made in Japan; Report of Magnetic Observations; Report of Agricultural Meteorology; and Report of Aerological Meteorology.

Comment--In 1944, the Navy transferred its Meteorological Department to quarters in the Central Meteorological Observatory. When Japan was occupied by American troops, the Observatory was placed under guard. Classified as a military objective, a considerable amount of meteorological equipment was confiscated. Oceanographic equipment, being the property of the Central Meteorological Observatory, was not disturbed.

The Imperial Fisheries Experimental Station (the Suisan Sikendyô)

History or origin--Established in 1929.

Location--Tukisima, Kyobashi-ku, Tokyo. 3 Gochi.

Organization to which attached--Ministry of Agriculture and Forestry.

Purposes--Investigations, researches, and experiments on fisheries and their utilization.

Appropriation--720,000 yen (fixed annual grant).

Scope of activities--Physical and biological oceanography, fishing, fish culture, preservation of fish, utilization of fish and other marine products, development of fishing boats, etc. War service restricted to intensified attempts to develop deep water fishery.

Equipment--Laboratories and experimental stations; head office of main station; three laboratory buildings; experimental model basin (approximately 10 × 150 meters); two experimental factories; freezing room for experiments; station vessel, the Soyo-Maru, 202 tons. New building expansion planned for 1947, to permit increased work on problems of the fishing industry.

Branch stations--Three previous branch stations were abolished, the Kisaki Station in 1937, the Toyohasi and Otyo Stations in 1940, because the locations were not best suited to the work required, and because Prefectural Fishery Experiment Stations had taken cognizance as needed. The Kasaoka Station, staff of five persons, has been continued for shellfish culture only in Okayama Prefecture. Two new branches have been established: (1) Ueda Station (1937) in Nagano Prefecture for fresh water fish culture, seven persons on staff; (2) Nanao Station (1939) in Ishikawa Prefecture for the development of marine products in the Japan Sea, five persons on staff.

Staff--Total personnel approximately 120, including the crew of vessel; scientific staff of 21 experts and 14 assistants; Director, Dr. N. KASUGA; Fishing, M. SAKAI; Fish Technology, KINTARO KIMURA, H. HIGASHI, and K. TANII; Pisci-culture, S. NAKANO and S. FUJIMORI; Physics, I. GENSHO; Chemistry, Dr. M. MIGITA; Biological Oceanography, Dr. KINOSUKE KIMURA, and Dr. T. HANAOKA; Physical Oceanography, Dr. KINOSUKE KIMURA; In charge of machinery, Dr. I. GENSHO; Biology, T. SHIMAZU; in charge of branch stations; at Kasaoka, D. KUSAKABE; at Veda, M. KAWAJIRI; at Nanao, Y. SUEHIRO; Captain of M. S. Soyo Maru, K. IMAMURA; in charge of fishing boat, S. KURITA.

Provision for publication of results--Journal of the Imperial Fisheries Experiment Station; Fisheries Investigation (Supplementary Report); Semi-annual Report of Oceanographical Investigation; Monthly Oceanographical Chart (in sheet).

Vessel operations--The ocean survey vessel Soyo-Maru engaged in ocean investigations in connection with the fisheries. The Navy on occasions requested that observations on physical oceanography be made in connection with the Institution's own program. This was optional with the Institute, however, as the vessel was at no time placed at the disposal of the Navy. In this respect it was unique, as vessels of all other institutions were pressed into naval service when their services were required. The following observations by the Soyo-Maru were recorded in Navy records: May 19-July 2, 1938, 118 stations in Tokyo-Nansei Shoto area; June 4-August 2,

1939, 148 stations in Tokyo-South China Sea; August 22-September 22, 1939, 84 stations in Tokyo-Northern Kuriles; April 22-May 29, 1940, 116 stations in Southern Honshu-Borneo; February 5-22, 1941, 29 stations in Tokyo-Hokkaido; February 27-March 5, 1941, 22 stations in Tokyo-Kyushu-Guam (in cooperation with nine other vessels).

Effect of War on operations--The Institution continued operations throughout the War. The work of the *Soyo-Maru* was greatly reduced but not completely stopped. No services were performed for the Army or Navy other than acquisition of oceanographic data. The wartime objective of the laboratory was to increase the fishery, and special work consisted principally of experiments on deep-sea fishing to 1000 meters by long-line trawls. The Semi-annual Reports were published until October 1943, and the Journal and Supplementary Report until March 1943. Routine coastal observations supplied by prefectural vessels have continued without interruption, but material since 1943, when the last data were published, has remained unorganized. Studies on the texture of the bottom were made some 20 years ago and published in Institute reports. There have been no studies on animal sounds, fouling, or other subjects not applicable to the fishery.

Imperial Fisheries Institute (the Suisan Kôshûjo)

Origin--Established in 1897.

Location--8 Eichujima, Fukagawa, Tokyo.

Organization to which attached--Ministry of Agriculture and Forestry.

Purpose--Education in science and art of the fisheries and the study of the profound theories on them, along with the formation of character.

Scope of activities--Fishing, technology of fisheries, pisciculture, physics and chemistry, mechanics, oceanography, zoology and botany, bacteriology, economics, and laws.

Equipment--Two main buildings, including 51 classrooms, 42 laboratories, a large auditorium, and 40 other rooms.

Vessels--*Unyo-Maru*, a training ship used for instruction in seamanship; *Shun kotsu-Maru*, a training ship of 500 tons, borrowed from the Ministry of Agriculture and Forestry; *Shinyo-Maru*, a trawler of 480 tons used for training in fishery methods. (The former training ship *Hakuyo-Maru* was sunk by an allied submarine in Borneo waters in March 1944, while serving as a Navy transport. It had been assigned to the Navy in February 1943.)

Branch stations--(1) Training Station at Tateyama Bay, Tiba Prefecture, used for training and experimental purposes; (2) Marine Biological Laboratory at Kominato Bay, Tiba Prefecture, used by students of pisciculture (see Kominato Marine Biological Laboratory); (3) Training Station at Yosida, Siduoka Prefecture, research on rearing of warm water fish; (4) Training Station at Oidumi, Yamanasi Prefecture, research on rearing of cold water fish; (5) Training Station at Numazu, Siduoka Prefecture, research and training of students of technology; (6) an oyster experimental station at Kanagawa, Kanagawa Prefecture, has been abolished, and possible transfer to Tiba is under consideration.

Appropriation--*Year*	*Regular budget*	*Special work*	*Total*
	yen	yen	yen
1940	437,880	76,169	564,049
1941	532,841	57,586	590,427
1942	539,754	23,198	562,952
1943	567,949	100,909	668,858
1944	620,131	56,501	676,632
1945	725,671	662,807	1,388,478

The large appropriation for special work in 1945 was for the following purposes: (1) Repair of Kominato Laboratory, damaged by a tidal wave following an earthquake in the spring of 1944; (2) conditioning of the old training ship *Shunkotsu-Maru*, borrowed from the Bureau of Fisheries to replace the *Hakuyo-Maru*; (3) establishment of an oyster culture station at Anegasaki, Chiba Prefecture; (4) accommodation of classes in navigation and fisheries, which had increased 50 per cent.

Staff--Director, YASUKICHI SUGIURA; Fishing Laboratory, Professors T. TANAKA, J. IHARA, T. SASAYAMA, Dr. H. KUSAMA, T. ARIHARA, Assistant Professors TAKIGUCHI, KANDA, SUDO; Technological Laboratory, Professors Y. MIYAMA, Dr. Y. SHIMIZU, T. KAWAGUCHI, S. IWAMOTO, Dr. KIMATA, K. SARUYA, Assistant Professor S. KAWAKAMI; Pisci-Cultural Laboratory, Professor Dr. J. HORI; Physical Laboratory, Professor M. TAUCHI, Assistant Professor K. MIYOSHI, Instructor Dr. S. KAMIYA; Chemical Laboratory, Professors D. AGR, T. OYA, Dr. Y. MATSUIKE, Dr. I. IKADA; Mechanical Laboratory, Dr. K. TOMIMASU; Oceanographical Laboratory, Dr. H. NIINO; Zoological Laboratory, Professor K. EBINA, Dr. T. MIMURA, Dr. D. INABA, K. MATSUBARA, Dr. I. KUBO, I. MATSUI; Botanical Laboratory, Dr. S. UEDA, Dr. K. ONDA; Bacteriological Laboratory, Professor T. MIURA, Dr. S. TANAHASHI, F. KATAYAMA, Y. KOISHI, Dr. S. OKAMOTO, Experts T. KIMEGORI, S. TSURUDA, YAMAGUCHI; Pelagic Fishery, Professor T. TAJIMA.

Provision for publication of results--The results of studies in the Institute are published in the Journal of the Imperial Fisheries Institute.

Vessel operations--The Institute utilized its vessels solely for student training cruises and never took ocean data except when requested by the Navy, in which case the Navy sent its own investigators to make observations and return results to the Hydrographic Office, Tokyo. The two vessels were used in the following areas: Hakuyo-Maru (prior to being sunk in March 1944): February 1-22, 1939, 24 stations in the Yellow Sea; November 23, 1940-January 9, 1941, 73 stations in the China Sea-Gulf of Siam; October 12-December 3, 1942, 113 stations in the East Indies-South China Sea. Shinyo-Maru: January 28-March 24, 1943, 167 stations in Nansei Shoto-Formosa.

Present status--A part of the buildings were occupied by the Seventh Cavalry Squadron on 21 December 1945, and the Unyo-Maru has since been transformed into a Red Cross canteen.

Misaki Marine Biological Station (Misaki Rinkai Jikkenjo)

History or origin--Founded in 1885.

Location--About 60 km south of Tokyo, Koaziro, Misaki-mati, Miura-gun, Kanagawa-ken.

Organization to which attached--Imperial University of Tokyo.

Purposes--Research by investigators associated with the laboratories and institutes of zoology, botany, fisheries, and medical sciences of the University, and visiting investigators; laboratory for college students of zoology; summer courses; staff and students of Biology Department of Faculty of Science and Fishery Department of the Faculty of Agriculture.

Scope of activities--Marine biology, oceanography, and allied sciences. Aquarium and museum are open to the public; summer courses in marine zoology for public and high school teachers; oceanographic observations; seismological observations; research facilities extended to visiting investigators. At present (January 1946) the aquarium is closed.

Equipment--Laboratory building, reinforced concrete 59 m × 13.5 m, with floor space 1000 sq m including chemical, physiological, and oceanographical rooms besides general laboratory; office and laboratory, wood, 12 × 9 m; aquarium-museum building, reinforced concrete, two stories, 29.7 m × 7.2 m, with floor space 363 sq m; the seismograph room; three dormitories, including residence for investigators; wooden cottage for staff; motor boat; rowboats.

Staff--Director, Dr. Y. K. OKADA; Resident Chief, Dr. K. KIKUCHI; Assistant, T. T. IIDA; Lecturer, Dr. K. DON; and seven assistants.

Provision for publication of results--Journal of Faculty of Science, Section IV, Tokyo Imperial University.

Effect of the War on operations--The Station was not used for research work after February 1945, when it was offered for the use of the Japanese Navy. All records were removed to Tokyo Imperial University. In January the property was returned to the University by United States Military Forces, and preparations are being made for complete resumption of operations soon. Dr. K. DON is at present (March 1946) in residence at the laboratory.

Kominato Marine Biological Laboratory

Location--On the sea shore of Kominato Bay, about 1.6 km south of Awa-Kominato Railway Station, Chiba Prefecture, and about 121 km from Tokyo via the Boso Railway Line.

Organization to which attached--Imperial Fisheries Institute, Tokyo.

Purposes--Research and instruction in marine biology.

Scope of activities--Researches in biology, under which planktology and biology of fishes are included; chemistry and physics of sea water, dynamical oceanography.

Equipment--Total site 5000 sq m; reenforced concrete laboratory building, including aquarium, two floors, 165 sq m, first floor aquarium with 11 tanks; second floor laboratory; wooden dormitory, two floors, 121 sq m, wooden bath house, building area 9.9 sq m; two wooden cottage residences; two engine houses; fish pond, about 40 × 20 × 8 ft; sea water tank, about 24,000 gallons capacity, reenforced concrete structure; boathouse; reenforced concrete pier, about 20 ft × 5 ft; research boat; library.

Staff--Director, Dr. HORI (remains at Tokyo); Local Members, Assistant Professor T. INO, Assistant NAKAMURA. The investigators also receive help in research from members of the Fish Culture Department of the Imperial Fisheries Institute and visitors from other institutions.

Provision for publication of results--Bulletin of the Japanese Society of Scientific Fisheries, issued in care of the Imperial Fisheries Institute.

(b) North of Tokyo

Onagawa Fisheries and Oceano-Chemical Laboratory

History or origin--First established in 1933 as the Oceano-Chemical Laboratory of the Chemical Institute of Tohoku Imperial University. In 1940, when an Agricultural Institute was established in the University, the Fisheries Laboratory was added at Onagawa.

Location--Onagawa, Ojika-gun, Miyagi Prefecture.

Organization to which attached--Chemical Institute and Agricultural Institute (Fisheries Division) of Tohoku Imperial University.

Purposes--Research in oceanography and fisheries biology.

Scope of activities--Research on life histories and methods of artificial culture of invertebrates and flat fishes. Genetics of Ostrea gigas.

Equipment--Two laboratory buildings, one story, floor area of large building 484 sq m, small concrete building 192 sq m; 14 rooms, of which eight are for biological research and two for chemical research, library, office, director's room, and darkroom; dormitory, one story, eight rooms; no student accommodations; capacity ten investigators; air, gas, electricity, running fresh and sea water; greenhouse and 17 outdoor culture tanks of concrete.

Vessels--Survey ship, Hogane-Maru, 13 tons, 35 hp diesel engines; rowboat.

Staff--In charge, Dr. TAKEO IMAI, three assistants, two laboratory aides.

Provision for publication of results--Reports of the Agricultural Institute (Fisheries Division) and Science Reports (Fourth Series) of Tohoku Imperial University.

Comments--In aircraft bombing attacks on 9 and 10 August 1945 on Navy vessels nearby, all laboratory windows were broken, and a motorboat (two tons) was destroyed, but the contents of the laboratory were not damaged.

Miyako Meteorological Observatory

History or origin--The Observatory was established in 1936. The principal object is to observe the temperature of sea water off the east coast of northern Japan every day when the weather permits.

Location--Miyako. 39°38′N, 141°59′E.

Organization to which attached--The General Central Meteorological Observatory, Tokyo.

Purposes and scope of activities--Meteorological and oceanographic observations.

Equipment--Besides a small laboratory for marine chemical work, the observatory operates a motor yacht, M. S. Kuroshio-Maru, 28 tons, and 6.8 knots in speed, length 18 meters.

Staff--Director, Y. TUDI.

Publication--The results of observations made at this Observatory are published in the publications of the General Central Observatory, Tokyo.

Hachi no-he Meteorological Observatory

History or origin--The Observatory was established for observations in the Hachi no-he area to a point 20 miles offshore.

Location--Hachi no-he, Aomori Prefecture, 60 miles north of Miyako.

Organization to which attached--The General Central Meteorological Observatory.

Purposes and scope of activities--Daily observations in Hachi no-he area, and occasional expansion northward to Cape Erimo and Muroran, Hokkaido. Oceanographic data acquired; temperature, salinity, waves, transparency, water color, chemical analyses (phosphate and silicate), and plankton (to be started).

Vessel--M. S. Oyashio-Maru, 17 tons, 30 hp, speed 6 knots, length 15 meters, built in 1936 and equipped with two hand sounding machines.

Comment--This institution was not visited. The above incomplete record has been taken from Science of the Ocean, v. 1, no. 3, 1941.

Marine Biological Station of Asamushi

Origin--Since its establishment in 1924, the Station has been an important center for marine biological research, some 200 papers having appeared by 1941.

Location--Asamushi, Aomori-ken, about 16 km northeast of city Aomori.

Organization to which attached--The Faculty of Science, Tohoku Imperial University.

Purposes--Major purpose, research; instruction in zoology, physiology, and planktology.

Scope of activities--Research in physiology, zoology, physiological chemistry, planktology, and oceanography.

Equipment--Laboratory building, two floors, 386 sq m of 14 rooms; eight research rooms for faculty, student laboratory, physiological laboratory, library, dark room, reception room, janitor's room; all furnished with gas, electricity, running sea and fresh water. (The undersea laboratory was abandoned after being damaged by storm seas.) Aquarium house, reenforced concrete, 238 sq m, business room, aquarium, museum; 24 tanks of various sizes, in which both fresh and sea water fishes are on display to the public; boathouse, 70 sq m; small fishing boat with portable motor; motorboat eight meters long, 20 hp gasoline engine, furnished with fish tank for transporting live fishes; motorboat seven meters long, eight hp engine; dormitory, two-story frame building, capable of accommodating 50 persons, area 636 sq m; four official residences, 116 sq m each, of three to five rooms.

Staff--Director, Dr. S. HOZAWA; Curator, Dr. S. KOKUBO; three assistants; one technical assistant.

Provision for the publication of results--Scientific reports of Tohoku Imperial University, B Series.

The Hakodate Marine Observatory (Hakodate Kaiyo Kishodai)

History or origin--Established in August 1942.

Location--Akagawadori, Kamedamura, Kamedagun, Hokkaido, Japan.

Organization to which attached--The General Central Meteorological Observatory.

Purpose--Research in marine meteorology and oceanography.

Scope of activities--Marine observation; meteorological observation; and research.

Equipment--In the Observatory, two rooms for research; in the Branch Office, one small room for research; residence for visitors; an observing ship, Yushio-Maru, of 150 tons.

Staff--Dr. M. NAKANO, Meteorologist (tides), Director; T. TAMURA, Oceanographer (plankton); R. TAGUCHI, Assistant (marine meteorology).

Provision for visiting investigators--No special provisions.

Income--Sources, the General Central Meteorological Observatory; amount, not fixed.

Provision for publication--Hokodate Kaiyo Kishodai Kaiyojiho (Oceanographic observations made by the Hakodate Marine Observatory); Hakodate Kaiyo Kishodai Yoho (Scientific reports of the Hakodate Marine Observatory).

Oceanographic Division, the Institute of Low Temperature Science

Established--1941.

Location--Sapporo, Hokkaido.

Organization to which attached--The Institute of Low Temperature Science, Hokkaido Imperial University.

Purpose--Physical oceanographical research.

Scope of activities--Research in oceanography, especially sea-ice, sea-fog, and oceanographic instruments.

Equipment--A part of building made of concrete and wood, 200 sq m, two floors including low temperature room (0 -40°C); four staff laboratories; laboratory for investigators (now occupied by United States Army excepting low temperature room and one staff laboratory).

Staff--Professor TAKAHARU FUKUTOMI; six research assistants (five temporary).

Income--4000 yen for 1945, from the Institute of Low Temperature Science.

Akkeshi Marine Biological Station

Origin--Established 1931.

Location--On the sea front of the Gulf Akkeshi, about 70 km east of Kushiro and 150 km west of Nemuro.

Organization to which attached--The Faculty of Science, Hokkaido Imperial University.

Purpose--Research, instruction for students.

Scope of activities--Research in biology and oceanography.

Equipment--Concrete building, 788 sq m, three floors including student laboratory, laboratory for investigators, five staff laboratories, aquarium room of ten tanks, library, public room, office, and motor room; small motorboat; two wooden residences.

Staff--Dr. TOHRU UCHIDA, Director; MAYUMI YAMADA and WAZUMI KUBO (temporary), Associates; Professor SHIRO IKUDA, Assistant.

Provision for publication of results--Journal of the Faculty of Science, Hokkaido Imperial University.

Oshoro Marine Biological Station

Location--Village of Oshoro, about 15 km southwest of Otaru Harbor.

Organization to which attached--Institute of Fisheries, Faculty of Agriculture, Hokkaido Imperial University.

Purpose--Teaching and research; marine biology and oceanography.

Scope of activities--Classes in marine zoology (ten days), marine botany (ten days), planktology (seven days), oceanography (seven days), embryology (seven days); research by staff.

Equipment--Grounds, 9100 sq m; main building, 340 sq m; first floor - main laboratory room for students, four small laboratory rooms for staff members, aquarium room, store room, kitchen, lavatory, bathroom, and three private rooms for keeper; second floor - four bedrooms; two storehouses, 170 sq m.

Staff--Director, Professor S. SAITO. There is no full-time staff.

The Institute of Algological Research (Kaiso Kenkyujo)

History or origin--Established in May, 1933. A new laboratory was completed in April, 1937.

Location--Hunami-cho, Muroran, Hokkaido, Japan.

Organization to which attached--The Hokkaido Imperial University.

Purpose--Research work on the marine algae.

Scope of activities--Systematic, cultural, physiological, and ecological studies on marine algae. Year-round research; entirely botanical.

Equipment--In the laboratory, one large and two small rooms for research, three rooms for culture studies; two small boats; a lodging for visitors.

Staff--Y. YAMADA, Professor of Botany, Hokkaido Imperial University; Y. NAKAMURA, Assistant.

Provision for visiting investigators--No special provisions.

Income--Sources, Hokkaido Imperial University; amount, not fixed.

Provision for publication of results--Journal of the Faculty of Science, Hokkaido Imperial University.

(c) West of Tokyo

Shimoda Marine Biological Station

History or origin--Established in 1933.

Location--Shimoda-Machi, Shizuoka-ken, Japan.

Organization to which attached--Tokyo University of Literature and Science.

Purpose--Research; instruction in zoology, botany, oceanography, geography, etc.; and science education on marine subjects.

Scope of activities--At present limited to zoological research, but as soon as possible it is intended to continue the following: Investigations in physiology, biochemistry, ecology, experimental studies of animals and plants, meteorology, oceanography, geography, geology, terrestrial magnetism, earth current, atmospheric electricity, etc.

Equipment--Sea water and fresh water are supplied for every laboratory; two gasoline motorboats (16 and five hp), and four collecting boats; an aquarium is attached. Some damage was suffered by the establishment due to Japanese military occupation.

Staff--Director, Dr. TAKATSUKI; Assistant, Dr. E. SAWANO; Mr. NAKAJIMA, Demonstrator (at present on leave).

Provision for the publication of results--Tokyo Bunrika Daigaku (University of Literature and Science), Science Reports.

War record--No work was carried on due to occupation of the building by Japanese coastal defense units.

Mitsui Institute of Marine Biology

History or origin--Established and opened in 1933 by TAKANAGA MITSUI.

Location--Susaki near Simoda, Kamo-gun, Siduoka Prefecture.

Organization to which attached--Independent institution.

Purposes--Research in marine biology.

Scope of activities--Researches in marine biology in general, planktology, algalogy, physiology, and oceanography; biological survey of the neighboring waters, especially of deep-sea fauna of Suruga Bay. Fellowships were awarded annually prior to the War by the Committee of the Institute to research workers desiring to investigate marine material in the Institute.

Equipment--Laboratory building, reinforced concrete, two floors, 297 tubo (one tubo 6 × 6 ft), of 25 rooms; nine research rooms, two libraries, three storerooms, two constant temperature rooms, two seismological observatories, office, public hall, museum, engine room, aquarium room, boathouse, janitor's room; all furnished with running sea and fresh water; small motorboat and a few rowboats for collection and oceanographical observation.

Staff--Director, Professor IKUSAKU AMEMIYA, Tokyo Imperial University (1936 -); OTOHIKO TANAKA (oceanography and planktology); SOKITI SEGAWA (algalogy, on leave at present); KOJIRO KATO (zoology, on leave at present); Clerk, DAISAKU SAKATA.

Provision for visiting investigators--At least three can be accommodated.

Income--Sources, provided from a grant by TAKANAGA MITSUI, future amount uncertain.

War record--Closed in 1943. The clerk, D. SAKATA, maintained the building for student use until February 1946, when the Laboratory was reopened under the directorship or Professor AMEMIYA. The prewar staff will be reappointed.

Sugashima Marine Biological Station

History or origin--Established in 1941.

Location--Sugashima, Mie Prefecture.

Organization to which attached--Faculty of Science, Nagoya Imperial University.

Purpose--Research.

Scope of activities--Chemical and biological research in local waters.

Equipment--Laboratory, 308 sq m; dormitory, 178 sq m; motorboat; three rowboats.

Staff--Director, Dr. YUJI SHIBATA (Geochemist); Assistants, Dr. M. SUGIYAMA, Dr. K. SUGAWARA (Geochemists); Postgraduate student, MIKI AKINO.

Provision for publication of results--As yet there have been no publications.

Imperial Marine Observatory, Kobe

Origin--Established in 1919.

Location--7 Chome, Nakayamate-Dori, Kobe.

Organization to which attached--General Central Meteorological Observatory, Department of Transportation.

Purposes--Marine meteorology and oceanographic investigations.

Equipment--Nine sections (about half of the buildings were destroyed by air raids) as follows: (1) Navigation Section, completely destroyed; (2) Weather Chart Section, completely destroyed; (3) Marine Meteorological Section, partially destroyed; (4) Physical Oceanography Section, slightly damaged; (5) Chemical and Biological Section, slightly damaged; (6) Meteorological Observation Section (inland), partially destroyed; (7) Instrument Calibration Section, partially destroyed; (8) Library, partially destroyed (oceanographic publications lost); (9) Ship (M. S. Shunpu-Maru), 124 tons, length 27.4 meters, partially damaged and now under repair.

Staff--Dr. K. KOENUMA, Director and Physical Oceanographer; Y. MATSUDAIRA, Oceanographer (biologist and chemist); T. SIBATA, Meteorologist; Z. YASUI, Oceanographer; Y. SAITO, Oceanographer; N. YAMAMOTO, Meteorologist; T. SINOZAKI, Meteorologist; G. HORIUCHI, Meteorologist.

Staff members killed in air raid--T. SANO, Director and Meteorologist (acting in absence of Dr. UDA, who was in military service, but is now on sick leave); Y. YANAGISAWA, Biologist; Y. MIMURO, Meteorologist; M. KINOSHITA. (The successive Directors of the Observatory following Dr. T. OKADA were Dr. Y. HORIGUCHI, Dr. M. UDA, Mr. SANO, and Dr. K. KOENUMA.)

Present status of Institution (February 1946)--The vessel is undergoing repair. No building repairs have yet been undertaken. Plans for restoration have been prepared for submission at the next Diet, but its action cannot be predicted. Most of the Institution's stock of publications was burned.

Provision for the publication of results--Annual Report; Memoirs of the Imperial Marine Observatory; Daily Weather Charts of the North Pacific; Journal of Oceanography; Tidal Observations; Miscellaneous Reports of the Marine Observatory (Kaiyo Kishodai-Iho).

Institute of Physical Oceanography

History or origin--Established 1921.

Location--Imperial University, Kyoto, Japan.

Organization to which attached--Imperial University, Kyoto (One assistant remains at the Osaki Tidal Station).

Purpose--Instruction and research.

Scope of activities--Physical oceanography in general.

Equipment--Ordinary equipment for research in physics.

Staff--All staff members are in the Department of Science at the Kyoto Imperial University. Acting Director, YOSHIKAZU TOYOHARA. Other members include TOHICHISO TAKEGAMI, KINZO SENO, AKIKAZU ODANI.

Income--About 3000 yen annually from the Government.

Provision for the publication of results--In Memoirs of the College of Science, Kyoto Imperial University, Series A. There have been no publications since 1932.

Seto Marine Biological Laboratory (Seto Rinkai Kenkyusho)

Origin--Operations instituted in 1922.

Location--Seto-Kanayama, Wakayama ken, on the west coast of Kii Peninsula, about 128 km south of Osaka.

Organization to which attached--Faculty of Science, Kyoto Imperial University.

Purposes--Research work on marine biology; instruction to students of Kyoto Imperial University.

Scope of activities--Researches in marine biology, including taxonomy, morphology, embryology, ecology, physiology, planktonology, etc.; lectures, laboratory courses in marine biology for University students; special courses in marine biology for teachers of middle and primary schools, usually attended by about 30 persons; exhibit of marine life for public.

Equipment--Buildings are all wooden and one-storied; students' laboratory, 220 sq m; research laboratory, 264 sq m; dormitory, 395 sq m; residence for resident members, 61 sq m; two motorboats; three rowboats; library, 13 sq m; aquarium building, 18 sq m; museum, 400 sq m.

Staff--Director, Dr. T. KOMAI; Lecturer, FUJIO UCHINOUMI; Assistants, K. NOZAWA, N. TAKEDA; Technical Assistants, T. HABE, Miss T. KASUYA; janitor and cook.

Provision for visiting investigators--Ten at most; usually about five.

Provision for publication of results--Mostly in Memoirs of the College of Science, University of Kyoto, also in other journals.

Onomichi Marine Biological Laboratory

History or origin--Established in 1939.

Location--Onomichi, on the Inland Sea, Honshu.

Organization to which attached--Hiroshima Imperial University.

Purposes--Marine biological research.

Scope of activities--Chiefly studies on the local marine fauna. Open all year.

Equipment--One building; motorboat.

Staff--Director, Dr. I. TAKI (Biologist); one assistant.

Amakusa Marine Biological Laboratory (Amakusa Rinkai Jikken-Jo)

History or origin--Established in 1928.

Location--Tomioka, Amakusa, Kumamoto ken, Japan, about 31 km southeast of Nagasaki.

Organization to which attached--Kyushu Imperial University.

Purposes--Researches by investigators associated with the laboratories and institutes of zoology, botany, physiology, biochemistry, anatomy, and pathology of the University, and of other universities and colleges.

Scope of activities--Chiefly the survey of the marine fauna and flora around Tomioka and its vicinity. Casual visitors may take up any field of research in marine biology, oceanography, and other related branches of science.

Equipment--Wooden laboratory, two stories, floor area 100 sq m; janitor's house and kitchen, one story, 66 sq m; dormitory, wooden, 100 sq m; land area about 62,000 sq m (laboratory partially destroyed by aircraft bombing followed by storm damage, no repairing yet considered, janitor's house damaged).

Staff--Director, Professor H. OSHIMA; Member of Council, Professor R. KOKETSU (one member, a professor in Kyushu Imperial University); administrator; assistant; janitor; part-time collectors and helpers. Scientific investigators are members of the Science Faculty and the Fisheries. Director, Professor H. OSHIMA, will resign in March 1946 due to age (61 or 62 years, age limit in Japan). The new Director will be selected from eligible senior professors; probably Dr. K. UCHIDA or Professor J. OYAMA.

Income--Not fixed.

Provision for the publication of results--The Journal of the Department of Agriculture of Kyushu Imperial University, and Magazine of the Zoological Society of Japan, are used mostly, but some are published in Records of Oceanographic Works in Japan.

(d) Korea

Fisheries Research Station (formerly the Fisheries Experiment Station of the Government-General of Chosen)

History or origin--Established in May 1921.

Location--Fusan, Korea.

Organization to which attached--The Government-General of Chosen.

Purposes--Scientific researches in oceanography, marine biology, and aquatic products for the promotion of the fisheries.

Scope of activities--Chosen and its adjacent waters.

Equipment--Main building in Fusan consists of laboratories for (a) fishing research and the study of suitable fishing boats, (b) chemical and physiological research, (c) biological and agricultural researches, and (d) oceanographical research. One small building was added during the War for investigations on the biology of mud flats. Three research vessels, (a) Misago-Maru, a steel motor ship of 153 tons for oceanographical observation, (b) Otori-Maru, a wooden motor ship of 40 tons, and (c) Hayabusa-Maru, a wooden motor ship of 31 tons, both for fishing researches. These vessels were not damaged in the War. Branch Station at Chinkai for fish culture has (a) biological laboratory, and (b) ponds for fresh water fish culture. Branch Station at Seishin (North Korea), for fishery industry studies; has (a) chemical laboratory, and (b) factories. Branch Station at Gensen, fishery industry problems. Branch Station at Ginsen, propagation of edible bivalves on mud flats.

Prewar organization--Four departments: Fishery Department; Oceanographical Department; Chemical and Physiological Department; and Biological and Aquicultural Department.

Provision for visiting investigators--None.

Provision for publication of results in the past--Bulletin of Fishery Experiment Station of the Government-General of Chosen; Annual Report of Hydrographic Observations; Oceanographic Charts; and other journals.

Postwar status of the Station--As of February 6, 1946, five members of the wartime Japanese scientific staff were continuing their work as in the past, but under United States Military Government supervision. Seventy-five Koreans were also employed and operated under supervision of the Military Government. The Station and its contents (apparatus, publications, and records) are intact.

New organization plan--Fisheries Research Station: President, MON K. CHUNG; Advisor, K. FUJIKAWA (Japanese). Main Station (Fusan): Industry Division; Head not yet chosen, Vice-chief C. H. CHANG, Japanese members K. FUJIKAWA, K. KASHIWADA, M. WADA; Fishery Division; Head not yet chosen, K. K. KIN; Biology Division; Head, President T. E. CHUNG; Economy Division; Head not yet chosen, A. P. AN; Hydrographic Division; Head not yet chosen, S. K. NAN, Japanese K. NISHIDA and T. NAKAI; General Affairs Section; Head, K. S. CHI; Examination Division; Head not yet chosen; Branch Station (Tchungjin); Head not yet chosen; Branch Station (Wunsan); Head not yet chosen, I. T. CHUNG; Branch Station (Mocpo); Head not yet chosen, T. KAN; Branch Station (Intchun); Head not yet chosen, O. O. HAHU.

(e) Formosa

Formosan Government Marine Fisheries Experiment Station (Kiirun)

Location--On the seashore at Senton, Kiirun.

Founded--1922 by the Japanese Government.

Organization to which attached--Formosan Government Bureau of Fisheries. (Chief of Bureau of Fisheries also serves as Director of the Station.)

Purpose--Oceanic biology and oceanography. Research on the biology of fishes and the fisheries of the waters surrounding Formosa.

Scope of activities--Investigation of fishing grounds, methods, and oceanographic work. Also experimental fisheries work and fish culture; handling and shipping of fishery products.

Equipment--One main building; two residences (accommodations for 20 people), cold storage building, experimental factory for canning.

Vessels--Ocean-going steam vessel, Sho-nan Maru, 500 tons.

Organization--Originally there were three divisions: Fishing (Oceanography), Fish Culture, and Manufacturing. After a recent reorganization the following divisions were established: (1) Biological Division (includes former Fish Culture branches); (2) Oceanographical Division (includes former Fishing Division); (3) Chemical Division (includes former Manufacturing Division).

Branch laboratories--(1) Formosan Government Fresh Water Fisheries Experiment Station (Toyn), belongs to Fish Culture Division and is limited to pond culture problems; (2) Formosan Government Brackish Water Fisheries Experiment Station (Anping, near Tainan). The Fish Culture Division is located here [culture of Chanos chanos (Forskal), oyster, shrimp, and crab].

Staff--Only two scientists were on the staff during the War. Total staff about 100, including vessel's crew, laborers, etc. There were about seven scientists on the staff prior to the War. Most recent Director, Dr. SOGO TETSUMOTO (Chemist and Bacteriologist); Dr. H. NAKAMURA (Biologist and Icthyologist) in charge of the Oceanographical Division. There is no information on the present whereabouts of the wartime staff or the present postwar organization.

Provision for visiting investigators--None.

Provision for publication of results--Reports of the Fishery Experiment Station of the Formosan Government, published irregularly. It contains the Oceanographic Reports. All the reserve stock of the publication was located in the Bureau of Fisheries in Tokyo and was destroyed by fire during an air raid.

(f) Palao Islands

Palao Tropical Biological Station

Location--On Korror Island, situated close to the main island of Palao, the South Sea Islands of former Japanese mandated territory.

Organization to which attached--The Japan Society for the Promotion of Scientific Research, Tokyo.

Purpose--Major purpose, research on biology in tropical waters with special reference to coral reefs.

Scope of activities--Researches in ecology of coral polyps and of reef formation, in physiology of growth, development, and reproduction in each coral species, in physics and chemistry of coral skeleton; and general biological and oceanographical survey necessary for investigation of the above mentioned fields.

Equipment--One-storied frame laboratory building, about 7 m × 11 m of a single large laboratory and a small darkroom for photographic work.

Vessel--During the War oceanographic work was carried on for the Navy by the Zuiho-Maru, Palao Government vessel.

Staff--Director, Professor S. HATAI; three commissioners (two in Palao, one in Sendai); two assistants, S. KATO and M. KUMAMO; two janitors. Professor HATAI remained as Director until the laboratory closed, and now resides in Tokyo.

Provision for visiting investigators--Four could be accommodated, including the staff and research members sent by the Society.

Provision for the publication of results--The Palao Tropical Biological Studies, issued by the Japan Society for the Promotion of Scientific Research, Tokyo.

War record--The laboratory closed in 1941, and in 1942 was occupied by the Japanese Navy. It was completely destroyed by aircraft bombing in 1944.

Reference

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U. S. Navy Department,
Washington, D. C.

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COOPERATION OF JAPANESE OCEANOGEAPHERS WITH ARMY AND NAVY DURING THE PACIFIC WAR

Koji Hidaka

(Dedicated to the American Oceanographers)

The cooperation of Japanese oceanographers with the Army and Navy was not really active before 1944. This was because both Army and Navy had their own scientific staffs and institutions whose equipment, facilities, and money by far exceeded those of universities and civil institutions. These military institutions exercised almost a monopoly on facilities before and during the War. If scientists other than those belonging to the Navy and Army wished to make researches, they encountered difficulty in finding apparatus, materials, and assistants. New graduates from the universities all entered the Army and Navy in recent years. They were indeed made to work in these institutions where there were, for the most part, no able scientific staffs and the efficiency of the researches was poor. Most professors in the universities were thus left without assistants and materials. For this reason, it was almost impossible for them to continue their research without having some association with military and naval institutions. The staffs of the latter, however, were not necessarily investigators of the first rank and had a tendency to prevent experienced scientific men from entering their institutions. Most had entered the Army and Navy from ten to twenty years ago, when few capable university graduates cared to join voluntarily. Some of the young scientific officers (graduates of recent years) had, of course, good qualifications because almost all were graduates of universities and colleges but the lack of capable senior staff members prevented them from utilizing their abilities freely.

In the field of oceanography, things were the same. We had no positive cooperation with the Army and Navy before the end of 1943. In September 1942 Dr. MITITAKA UDA, who was Director of the Imperial Marine Observatory, Kobe, and a very able oceanographer, was called into the Army as a sublieutenant of an aircraft gun unit and went to Sumatra. Afterwards, he was transferred to Singapore as a member of a weather group and sent back at the end of 1944 to Hiroshima, as a sublieutenant of the Army Transportation Service. Here he was an advisor of Marine transportation and carried on research on waves in relation to transport ships. He advised the utilization of the Kurosio (Japan Current) for the transportation of goods from Formosa, Nansei Syoto, etc. to Japan proper. Afterwards this problem was discussed seriously also by other oceanographers but without materialization.

Acoustic apparatus for detecting submarines has been studied in the Naval Technical Institute, and a branch of this institution was established in August 1943 on Enoura Bay near Numadzu for the special purpose of improving the acoustic apparatus. This branch institution soon began operations, and in early autumn Lieutenant Commander L. NAMBA reported to Dr. S. FUJIWHARA, Director of the General Central Meteorological Observatory, that in the hydrophones placed in the sea adjacent to Enoura, strange noises disturbing the function of the hydrophones were caught every night at certain definite hours. He then asked the Director to determine the sources of these noises by hydrographical research in this area. For this purpose an oceanographical survey of this bay was carried out in December 1943 by the members of the General Central Meteorological Observatory on board the R. S. Asasio-Maru. The true nature of the noises was not determined easily. S. MIYAKE and Y. TAKENOUTI took leadership in this expedition. On December 27, 1943, scientists were called to the Naval Technical Institute, Meguro, Tokyo. The chief members were Drs. H. NAGAOKA, H. YAGI, S. FUJIWHARA, T. NOMITSU, K. HAYASHI, K. HIKAKA, Y. MIYAKE, and Y. TAKENOUTI. Vice-Admiral Viscount Dr. T. TOKUGAWA, Director, Rear-Admiral T. MIYAZAWA and Capt. T. KUYAMA were the chief hosts. Besides these, there were present some authorities from naval operations. We were told that the audibility of the acoustic apparatus considerably fluctuates according to the hydrographic conditions of the sea, the reason for them being quite unknown. Thereupon we were appointed to make clear the mechanism of this variation of audibility and to search for the relation between audibility and hydrographic conditions. The demand of the Navy involved very difficult problems. First, we had no definite idea about the propagation of acoustic waves in sea water. Secondly, it was very difficult to obtain a correct concept of the mechanism of these fluctuations. The naval specialists stated that there are regions of bad audibility in the sea just like clouds floating in the sky. Dr. FUJIWHARA said that it might be air bubbles contained in the uppermost layers of the sea that scattered the sonic waves, while MIYAKE insisted that bubbles would be almost absent, due to water pressure, in the subsurface layers. But the general opinion prevailed that it might be the turbulence in the water which disturbs the propagation of sonic waves. For these reasons it was very difficult to decipher the riddle of the sound by ordinary hydrographic observations of the type hitherto carried out. Therefore, a special apparatus for measuring the dissipation of sonic energy was supplied by the Navy. This consisted of a rod to which a hydrophone and transmitter were attached in a straight line and the rate of dissipation by water could be determined by observing the intensity of sonic waves at two different distances between the transmitter and hydrophone. The frequency used was 100 kc, which seemed to me rather high, though it was said to be an inevitable consequence for making the waves concentrate in one direction. The apparatus was used in a bifilar suspension from the ship and the observations were made from the surface to fifteen meters at one meter intervals.

The survey was again made in May 1944 by members of the General Central Meteorological Observatory on board R. S. Asasio-Maru. Of course, ordinary hydrographic observations were carried out simultaneously. Y. MATUDAIRA and Y. SAITO, of the Kobe Marine Observatory also carried out the same experiment in the Bungo Suido on board R. S. Syunpu-Maru. But since this queer phenomenon is micro-oceanographic, it was very difficult to make clear the mechanism by usual oceanographic survey alone. In the end, the general opinion was that the propagation of sound seems to be hindered by the presence of microscopic turbulence in the movements of the sea water. But it could also be said that the microscopic turbulence which seemed very conspicuous in this bay might not be so striking in the open sea where the fluctuations of hydrographic conditions are far less intense. We were told indeed by the Naval authorities that the reason why Enoura Bay was chosen for the experimental ground is its morphological condition; the depth is very uniform. But from the hydrographic point of view this bay can not be said to be very well fitted for this purpose, because there are several different masses of water; that is, the coastal water, Kurosio water, and the river water from the land. This system of water necessarily forms eddies along the boundary surfaces, and microscopic turbulence occurs there.

But the most effective factors in the open sea disturbing the audibility must, in my opinion, be the reflection of sound rays along the boundary surfaces between different water masses and the refraction of sound rays when the density of the sea water gradually changes vertically or horizontally. This view was firmly held by S. KUWABARA of the Hydrographic Department, Y. TAKENOUTI, and K. HIDAKA. This effect is found most intense in the uppermost layers of the sea where the vertical changes of temperature are most striking. To represent the effect of refraction, the vertical gradient of density was chosen and it was concluded that the more intense this gradient is, the worse is the audibility. The disturbance due to the reflection can be expected along the discontinuities between water masses, that is, the polar front, the boundaries between the Kurosio and the coastal waters, and the subtropic convergences.

To test these effects, joint experiments were carried out in Lakes Kawaguchi and Hakono several times by the Central Meteorological Observatory and the Naval Technical Institute. When there is discontinuity there, it is due to temperature stratification in the upper layers, since there is no salt in lakes, and other disturbing factors were thought to be less active. The results of the experiments were not negative.

Taking these circumstances into account, KUWABARA and TAKENOUTI drew at the beginning of 1945 synoptic charts showing the variation of audibility in different parts of the seas adjacent to Japan. KUWABARA, in his first chart published by the Hydrographic Department, considered the effect of refraction due to the vertical variation of density in the uppermost layers only, while TAKENOUTI'S bimonthly maps were drawn taking the effects of reflection, refraction, and turbulent eddies into account. These maps, however, were not prepared before the summer of 1945. Of course, these charts were scarcely used before the War ended on August 15, 1945.

As to the strange noises caught nightly in the hydrophones, Y. HIYAMA, Assistant Professor, Institute of Fisheries, Department of Agriculture, Tokyo Imperial University, a marine biologist, recognized them to be due to the fish "meagres" Sciaena schlegeli calling their mates.

In the fall of 1943, the Japanese Government, being frightened by the American Pacific operation, feverishly set about improving the scientific level of this country, and a fund was provided for this purpose. We scientists were requested to apply to the Department of Education for funds to perform the investigations which we thought necessary to the stage of the war at that time. I myself proposed a study of the coastal waves and breakers on the shore in order to determine the direction in which the depressions and storms exist. I intended to prepare for weather forecasting at the stage of the War when all the important islands would fall to the United States Forces. But sorry to say, my application was dismissed by the staff of the National Research Council. In 1944, I again emphasized the necessity of observations of coastal waves, and this item was finally adopted by the General Central Meteorological Observatory. Preliminary observations were carried out on the sandy beach of Shirahama on the east coast of Idu Peninsula in August 1944. The chief members were HIDAKA, TAKENOUTI, N. WATANABE, and K. HARAGUTI. At the same time, the Meteorological Service of the Army also appointed us to make a survey of the waves with reference to defense against the landing operations of American forces. They requested us to measure the heights and periods of the coastal waves and breakers. In reality these two elements determine the nature of the waves, since the wave-length and wave-velocity in deep water can be calculated from the period. The observations were carried out by establishing scaled poles in the water and reading them by naked eye or telescope. Afterwards the Land Defense Headquarters and subordinate commands also requested observations of the waves along the coasts of Kwanto District. The observations were carried out on the sandy beach of the Kashimanada coast north of Boso Peninsula in February 1945, and on the Kujukurihama (northeastern coast of Boso Peninsula) in March and May, 1945. The chief investigators were TAKENOUTI, WATANABE, and K. YOSHIDA.

The research on waves on these coasts is still being continued by the members of the General Central Meteorological Observatory and the Geographical Institute, Toyko Imperial University. Simultaneous observations of coastal waves at several places on the Sagami Bay were carried out in June and July 1945 and in January 1946 by the same members. From these observations of coastal waves, it is concluded that the effect of the wind on the height of surf near the shore is considerably smaller than the height expected from the relation between the waves and winds in the open sea.

It appears now time to give an account of the utilization of the ocean currents for the transportation of goods. As far as I know, this idea arose from the results of drift bottle experiments. In the winter of 1943-44, Dr. R. SEKIGUTI, Director of the Tokyo Astronomical Observatory humorously remarked that if we lost Formosa we would have no sugar at all. This conversation was soon discussed seriously, and I made a statistical investigation with available data on drift bottles, concluding that at the period of southeast monsoon, that is, from April to September, about 30 to 50 per cent of those goods set adrift near the northern end of Formosa will reach the coasts of Japan proper. I presented these results in October 1944 before a meeting of Committee of Geology and Geophysics, National Research Council. This conclusion was supported by Dr. K. KIMURA of the Government Fisheries Experimental Station, and I am told that Dr. UDA also planned the same. The above fact was reported by an Army scientist, who had been present at the meeting, to the staff of the Fuel Headquarters of the Army. It appeared to me that he was trying to materialize this plan. He said that the military authorities were hoping to bring gasoline from Formosa in this way. Meanwhile, air raids on Japan began on November 24, and soon the Philippines were lost. Transportation from Formosa was hopeless now. And as far as I know this plan had not an opportunity of being carried into execution.

On January 11, 1945, a meeting on this subject was held in the General Central Meteorological Observatory, and the members were the three personnel of the Army Fuel Headquarters and also M. UDA, K. KIMURA, S. YOSHIMURA, Y. TAKENOUTI, and I. Before the meeting, the military officers said they were flying to Formosa to execute this plan (but it appears to me that they never carried it out). They also asked us if it would not be possible to bring goods from Manchuria by this method. We replied that this was by far a safer plan, since it is known that almost 90 per cent of the drift bottles set adrift in the Japan Sea off the east coast of Korea reach the north coasts of Honshu. KIMURA prepared compact statistics for executing this plan.

On a snowy day in February 1945, I, accompanied by Drs. FUJIWHARA and SEKIGUTI recommended this plan to the Naval and Military Technical staffs. The reason why we recommended this plan again and again, and to different personnel, was that they were so inactive in adopting plans recommended by scientists. This, I suppose, was partly because the military men did not trust scientists and because the Japanese people in general were placed on a low scientific level. But the chief reason was that there were very few patriots among professional military men who dared to risk their reputations in executing this plan. They loved their lives and money and not their country and nation. They were always afraid of being dismissed if the execution of a plan was not successful.

Meanwhile Dr. R. KINOSHITA, Professor in Pathology, Osaka Imperial University, told me that most Japanese people were now losing their efficiency as the effect of hunger edema resulting from the lack of amino acids. He said if the present condition of public nourishment persisted until the end of the year, the health of the Japanese people would so decline that Japan would lose its working power. It was a serious question how to prevent so dangerous a state. KINOSHITA insisted that the only remedy for this was to import soy-beans from Manchuria, utilizing the currents in the Japan Sea. Based on these circumstances, KINOSHITA and I explained during March the importance of the transport of soy-beans from Manchuria to various personnel in Government, Army, and Navy. But there was no reaction. Dr. K. HAYASHI, Professor of the Osaka Imperial University, sailed himself to Korea in order to encourage the Army to execute this plan. But the result was negative.

At the end of February, the intensity of American air raids was suddenly enhanced and I moved to Nagano Prefecture on March 30, 1945 in order to be sheltered from the bombing. I taught oceanography to the University students who accompanied me in a rural, tranquil place, and my activity in this direction naturally died out. I believe that several scientists managed to materialize this plan, but I gave it up after I moved to Nagano Prefecture. I did my best as a scientist. Further effort had to be left to the leaders in the government. If this plan were not adopted, the Japanese people might lose their health towards the end of 1945. But our leaders seemed indifferent. This was a question of humanity, not of war itself, I felt. I really felt everything was against Japan. And the War came to an end on August 15!

The end of the War was a great event. Japan was beaten! The atomic bombs made a serious epoch, not only in the Pacific War, but also to the more important item, science. At the same time the end of the War was a very happy event to humanity. We always feel how barbarous war is! And how noble and glorious science and arts are! And how science and arts bring happiness to mankind and how the war is cruel to mankind.

On the night of August 15, I, in my rural residence in Nagano Prefecture, raised my glass and drank to the creation of a New Japan and a New World. I never felt the nobleness of science so deeply as I did that night. How complicated my feelings then were, I am sure, American people could never imagine. I venture to hope that the time will come as soon as possible when all the world recognizes the importance of science and arts to humanity and feels no necessity of cruel war.

Tokyo Imperial University,
Tokyo, Japan

(This communicated statement was obtained from Dr. HIDAKA, who is now Director of the Geophysical Institute of the Tokyo Imperial University by CHARLES J. FISH while on a Naval mission to Japan; open for formal discussion until January 1, 1947.)

Transactions, American Geophysical Union Volume 27, Number IV August 1946

OCEANOGRAPHY IN JAPAN

Charles J. Fish

Since 1929 oceanography has received more widespread attention in Japan than in any other nation, and virtually all has been financed directly or indirectly by the Government. The number of vessels (95) utilized by the Japanese Hydrographic Department alone for whole or part-time surveys during this period probably exceeded those of all other nations combined.

Open ocean investigations were carried on almost entirely by the Navy or under Navy control. Vessels pressed into the service of the Hydrographic Department included, in addition to 12 naval ships, seven survey vessels of other central government agencies, 30 prefectural station vessels, and 46 commercial craft. Of the latter, 22 were coastal fishing craft, 22 were killer ships of the whaling fleet, and two were merchant ships.

Extensive investigations were also made in home waters by the Hydrographic Department, but in addition seven central governmental civilian institutions, at least 24 prefectural fisheries experimental stations, and some 17 government-financed marine laboratories operated here during the periods when their vessels were not required for service with the Navy.

There was, however, little or no coordination between the oceanographic work of the Navy and that of other scientific institutions, even when vessels of the latter participated in naval work. Usually naval personnel were assigned to civilian vessels to carry out the Navy's program, and they returned all data to the Hydrographic Department. This immense mass of accumulated information, now in the possession of the United States Hydrographic Office, was never made available to civilians.

Nevertheless civilian oceanography continued to expand, and during the past ten years the following institutions have been established:

(1) Onomichi Marine Biological Laboratory of Hiroshima Imperial University, 1939.
(2) Nanao, Branch Laboratory of the Imperial Fisheries Experimental Station, 1939.
(3) Onagawa Fisheries and Oceano-chemical Laboratory, Tohoku Imperial University, 1940.
(4) Hachi no-he Meteorological Observatory, General Central Meteorological Observatory, prior to 1940.
(5) Sugashima Marine Biological Station, Nagoya Imperial University, 1941.
(6) Oceanographic Division, Institute of Low Temperature Science, Hokkaido Imperial University, 1941.
(7) Hakodate Marine Observatory, General Central Meteorological Observatory, 1942.
(8) Oshoro Marine Biological Station, Hokkaido Imperial University, date not known.

One important new scientific society, The Oceanographic Society of Japan, was founded in 1941 by H. TOMINAGA in an effort to establish a basis for cooperation between the three largest governmental oceanographic institutions, the Hydrographic Department, the General Central Meteorological Observatory, and the Imperial Fisheries Experimental Station. Headquarters are in the General Central Meteorological Observatory, and there are two publications, the *Journal* of the Oceanographic Society of Japan, and *Science of the Ocean*. Three volumes of the former and four volumes of the latter have appeared to date.

Five oceanographic institutions were damaged by aircraft bombing. In the raid on March 10, 1945 the greater part of the Hydrographic Department was burned, leaving intact only the main building, a foundry, and three storehouses. In another raid on Kobe about one-half of the buildings of the Imperial Marine Observatory were destroyed, the vessel *Shunpu-Maru* damaged, and four members of the scientific staff, including the acting director, T. SANO, were killed. On Kyushu the Amakusa Marine Biological Laboratory was partially destroyed by bombing and has subsequently suffered storm damage. At Onagawa on March 9 and 10, 1945, during an aircraft attack on naval vessels in the harbor, all laboratory windows were blown out and a motorboat was destroyed,

but the contents of the buildings remained undamaged. The Palao Tropical Biological Station was completely wiped out by bombing in 1944 after it had been occupied for two years by the Japanese Navy.

Five oceanographic institutions in the home islands have been occupied by Japanese or United States Military Forces. The Naval Meteorological Division of the Hydrographic Department became an independent naval department in 1944 and since then has occupied space in the General Central Meteorological Observatory. The Shimoda Marine Biological Station was taken over during the War by a Coastal Defense Unit, and in February 1945, a unit of the Japanese Navy occupied the Misaki Marine Biological Station. United States Military Forces now have quarters in the Imperial Fisheries Institute, the Oceanographic Division of the Institute of Low Temperature Science, and the Hakodate Fisheries College.

Yet, in spite of air raids and military occupation, civilian oceanography in Japan has suffered surprisingly little in the War. It was not until late in 1943 that the Army and Navy made appreciable use of civilian oceanographers, and then a relatively small number turned their attention to military problems. The others continued their prewar research, assisted until 1945 by generous grants from three national organizations.

All marine stations on the home islands are now either in operation or are planning to resume operations in the near future. The Hydrographic Department has been authorized to continue its work under the Ministry of Transportation. The scientific staffs remain largely intact, either at the laboratories or, in the case of those which have not yet reopened, at the parent universities where they are carrying on such of their studies as available facilities will permit at this time.

In most institutions on Honshu and Kyushu the scientists worked in unheated buildings during the past winter, but adversity and discomfort do not appear to have affected their morale. The only complaints heard concerned their inability to have papers published and the lack of foreign scientific journals since 1941. All plead for an early resumption of international exchanges.

U. S. Navy Department,
Washington, D. C.

(Manuscript received June 4, 1946; presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 27, 1946; open for formal discussion until January 1, 1947.)

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NOTES ON PARÍCUTIN LAVA

Austin E. Jones

Introduction--The writer was in the vicinity of Parícutin Volcano from February 18 to August 24, 1945, during the third year of the Volcano's existence. During this time the cone erupted explosively almost continuously, and lava flows were constantly advancing, but since the writer was occupied in maintaining a seismograph and magnetograph, his observations of movement of the lava were restricted to occasions when lava fronts were active near established trails. The observations in this paper are offered as a contribution to the mechanics of motion of lava flows.

Most of the lava was very rough and broken, and of the variety termed aa-rubble or aa-clinker, but some of it was aa-in-place [JONES, 1943].

Aa-rubble from moving lava--In July, a lava front moving down a short steep slope about 100 yards northwest of the foot of the main cone of Parícutin showed the mode of advance unusually well. The front was advancing about 20 feet an hour, somewhat more rapidly than usual, and the bright-red interior lava was exposed. The mechanism of advance is indicated diagrammatically in Figure 1, in which the blocks of solidified lava are numbered in order of relative age. It was apparent that the fragments numbered "1" to "7" under the flow had been in positions corresponding to blocks "8" to "15," and as the flow advanced had rolled successively down to the position of block "7." Some indication of liquid motion could be seen in the red lava under block "8," but the doughy material hardened quickly, and most of the movement resembled that in a rock pile pushed in front of a bulldozer. At the top of the flow near the front, where the lava was red, fissures were seen to open and deepen in the manner indicated between blocks "10" to "13;" the blocks curled off in a way that suggested exfoliation. Evidently at this stage in cooling the lava had hardened, but was not strong enough to withstand the stresses caused by differential cooling, which probably amounted to several hundred degrees. At intervals ranging from seconds to minutes along a hundred-foot front, red-hot pieces such as that indicated at "8" pulled off and rolled down among cooler pieces from the surficial crust, indicated by "14" and "15." In a short time this debris was covered by the advancing lava.

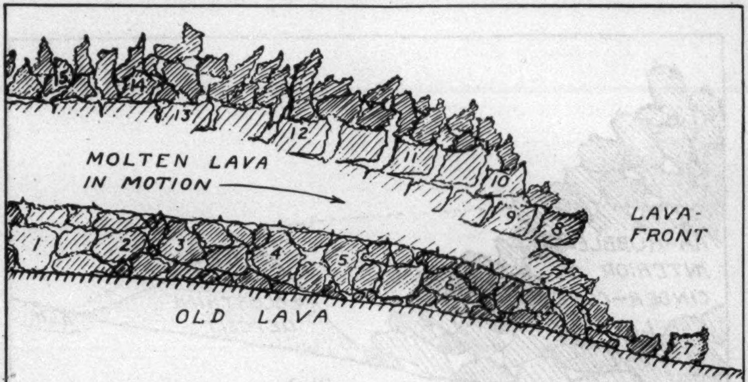

Fig. 1--Ideal cross section of a lava front and mode of break-up

The top layer or rubble, shown by "14" and "15" may have been formed in the same way that blocks "10" to "13" were, for near the orifice or boca the red-hot rubble appeared to be integral with the underlying lava. Within a very few feet of the orifice the surface lava appeared molten though viscous, but within 50 feet or less the red lava hardened enough to stand with a relief of about a foot. In daylight the lava appeared stippled red for several hundred feet, before the cooled rubble concealed the glow from all but the largest cracks. Tension cracks of the type described between blocks "10" to "13" apparently developed continuously between the point where the crust first formed and the front of the flow. The lava front approximately a mile from the source was about 30 feet high, and the surface rubble constituted about a third of the total thickness.

Advance of lava through mud--The advance of a lava front into mud was seen at a place where a flow had dammed a stream from Tancítaro Mountain and impounded mud and water. The mud was piled up in front of the lava as shown in Figure 2. The slope of the contact between the lava front and the mud could not be determined, and it may have been somewhat as indicated by the dashed line. There was, however, violent boiling under the lava front, and the writer believes that

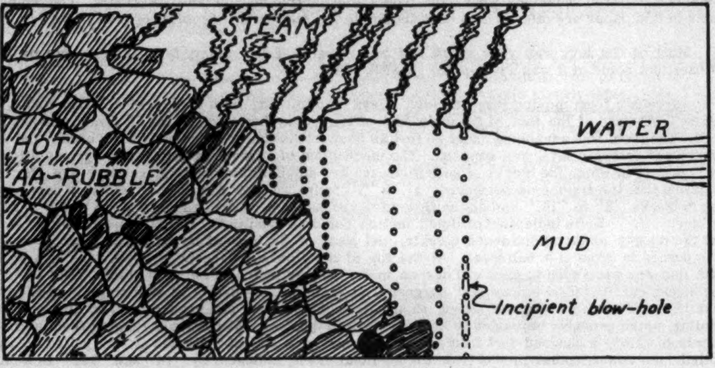

Fig. 2--Lava-mud contact observed at Parícutin Volcano

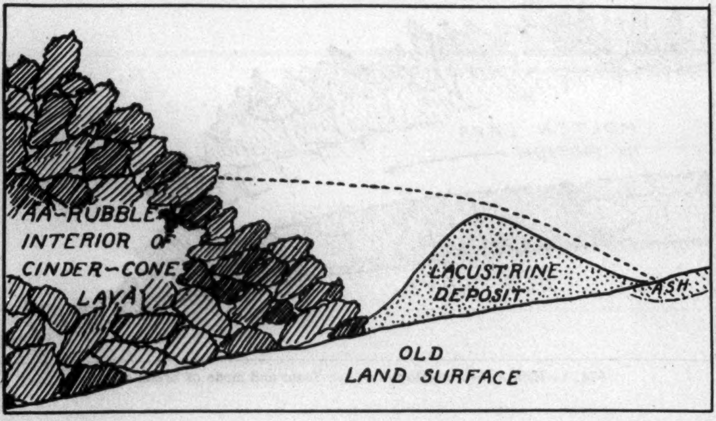

Fig. 3--Lava-mud-contact interpretation for Cinder Cone, California the steam pressure probably prevented penetration of mud very far into the lava rubble. Boiling several feet in front of the visible lava-mud contact suggests that the lava advanced under the mud, as indicated. The mud was rather thick, and formed semi-permanent vents filled with thin, bubbling mud; these vents appeared to be incipient blow-holes.

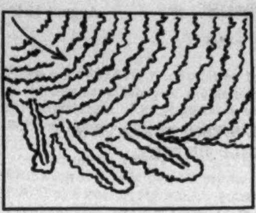

Fig. 4--Diagram of structural flow pattern on Parícutin lavas

Analogous relations were seen at Cinder Cone, California, where lava advancing over a lake bottom appears to have piled mud up much higher than at Parícutin. The probable original surface of the mud is indicated by the dotted line on Figure 3; the remnant left by erosion is several feet in height. An old steam vent reminiscent of the bubbling vents at Parícutin, but on a larger scale, was seen in the muds near Cinder Cone.

Patterns on surfaces of flows--While examining the flows from a helicopter at an altitude of several hundred feet, several geologists noted definite structural patterns on the surface of the flow of San Juan de Parangaricutiro in 1944. Figure 4 is a rough sketch drawn from memory to show the general relations. Aa-rubble lay in curving ridges across the direction of movement over the main part of the flow, but on the narrow projecting tongues the surface was largely formed of aa-in-place, and the ridges were longitudinal, resembling the pressure ridges described on other lava flows.

Reference

JONES, A. E., Classification of lava surfaces, Trans. Amer. Geophys. Union, pt. 1, pp. 265-268, 1943.

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A GENERALIZED GRAPHICAL METHOD FOR EVALUATING FORMATION CONSTANTS AND SUMMARIZING WELL-FIELD HISTORY

H. H. Cooper, Jr. and C. E. Jacob

(Published with the approval of the Director of the Geological Survey,
United States Department of the Interior)

Abstract--The capacities of a water-bearing formation to transmit water under a hydraulic gradient and to yield water from storage when the water table or artesian pressure declines, are generally expressed, respectively, in terms of a coefficient of transmissibility and a coefficient of storage. Determinations of these two constants are almost always involved in quantitative studies of ground-water problems.

C. V. THEIS [1935, see "References" at end of paper] gave an equation, adapted from the solution of the analogous problem in heat conduction, for computing the non-steady drawdown accompanying the radial flow of water to a well of constant discharge. This equation has been used successfully many times for determining coefficients of transmissibility and storage from observed drawdowns. As it involves a transcendental function known as the exponential integral and two unknown coefficients, one of which occurs both in the argument and as a divisor of the function, the coefficients cannot be determined directly. However, they may be determined by a graphical method devised by THEIS and described by JACOB [1940, p. 582] and WENZEL [1942, pp. 88-89]. This method requires the use of a "type curve," on which the observed data are superimposed to determine the coefficients.

Later, WENZEL and GREENLEE [1944] gave a generalization of THEIS' graphical method by which the coefficients may be determined from tests of one or more discharging wells operated at changing rates. This method requires the computation of a special type curve for each observation of drawdown used. It is without doubt a worth-while contribution to the quantitative techniques of groundwater hydraulics, but in tests that involve more than a very few discharging wells or a very few changes in the rates of discharge, the computation of the special type curves is necessarily so laborious as to make the method difficult to apply.

The present paper gives a simple straight-line graphical method for accomplishing the same purposes as the methods developed by THEIS and by WENZEL and GREENLEE. Type curves are not required. The writers believe that the straight-line method, where applicable, has decided advantages, in ease of application and interpretation, over the other graphical methods. However, as the method will not be applicable in some cases, it is expected to supplement, rather than supersede, the other methods. The method is designed especially for artesian conditions, but it may be applied successfully to tests of non-artesian aquifers under favorable circumstances.

This paper first gives the development of the method for tests involving a single discharging well operating at a steady rate, and then generalizes the method to make it applicable to tests involving one or more wells discharging intermittently or at changing rates. Examples are given to demonstrate the method.

Straight-line method for a single well discharging at a steady rate

When sufficient time has elapsed after an artesian well has begun discharging at a steady rate, the drawdown within a given distance increases approximately in proportion to the logarithm of the time since the discharge began, and decreases in proportion to the logarithm of the distance from the well. By virtue of this relationship, it is possible to determine the coefficients of transmissibility and storage of an aquifer from a simple semi-logarithmic plot of observed drawdowns.

The drawdown produced by a well discharging at a steady rate from an extensive artesian aquifer of uniform thickness and permeability is given by equation (1) [THEIS, 1935].

$$s = (Q/4\pi T)W(u)$$

$$= (Q/4\pi T)(-0.5772 - \log_e u + u - u^2/2.2! + u^3/3.3! - \ldots) \quad \ldots\ldots\ldots\ldots (1)$$

Here $u = r^2S/4Tt$, r = distance from the discharging well, t = time elapsed since start of discharge, T = transmissibility of the aquifer (discharge per unit normal width per unit hydraulic gradient), S = coefficient of storage (volume of water that a unit decline of head releases from storage in a vertical prism of the aquifer of unit cross section), and Q = discharge of the well.

For small values of (r^2/t) compared to the value of $(4T/S)$, u will be so small that the series following the first two terms in the series in equation (1) may be neglected. Thus, where values of (r^2/t) are relatively small, equation (1) may, for all practical purposes, be approximated as in equation (2).

$$s = (Q/4\pi T)[\log_e(1/u) - 0.5772]$$

$$= (Q/4\pi T)[\log_e(4Tt/r^2S) - 0.5772]$$

or

$$s = (Q/4\pi T)\log_e(4e^{-0.5772}Tt/r^2S) = (Q/4\pi T)\log_e(2.25Tt/r^2S) \quad \ldots\ldots\ldots\ldots (2)$$

The approximation will be tolerable where u is less than about 0.02. Converting to the common logarithm, we may rewrite equation (2) in any one of the three forms in equations (3), (4), and (5).

$$s = -(2.303Q/2\pi T)[\log_{10}r - (1/2)\log_{10}(2.25Tt/S)] \quad \ldots\ldots\ldots\ldots (3)$$

$$s = (2.303Q/4\pi T)[\log_{10}t - \log_{10}(r^2S/2.25T)] \quad \ldots\ldots\ldots\ldots (4)$$

$$s = -(2.303Q/4\pi T)[\log_{10}(r^2/t) - \log_{10}(2.25T/S)] \quad \ldots\ldots\ldots\ldots (5)$$

The only variables in these equations are the drawdown s, the distance r, and the time t. It is apparent that when t is constant, (3) will be the equation of the straight-line plot of s against $\log_{10}r$. Similarly, when r is constant, (4) will be the equation of the straight-line plot of s against $\log_{10}t$. Moreover, with r and t combined into the single variable (r^2/t), (5) will be the equation of the straight-line plot of s against $\log_{10}(r^2/t)$.

In each equation the slope of the corresponding straight-line plot is represented by the quantity on the outside of the brackets, and the intercept of the straight line on the zero-drawdown line is represented by the second term within the brackets.

As T is the only unknown in the quantity representing the slope, the coefficient of transmissibility is readily determined from a semi-logarithmic plot of observed data by equating the slope of the plot with the corresponding quantity in equation (3), (4), or (5), and solving for T. After T is determined, the only unknown remaining in the term representing the intercept will be S. Therefore, the coefficient of storage may then be determined by equating the intercept of the plot with the corresponding term, and solving for S.

The plots will be straight lines only where (r^2/t) is relatively small so that u is small. A measurement of drawdown that is made too soon after the discharge is begun, or too far from the discharging well, will plot not on the straight line, but on a curve asymptotic to it. However, in tests of artesian aquifers u becomes small soon after the discharge is begun, and hence in most cases little, if any, of the data will fall off the straight line.

The three types of graphs that correspond respectively to equations (3), (4), and (5) may be referred to as the distance-drawdown graph, the time-drawdown graph, and the composite-drawdown graph. The type of graph to be selected for determining the coefficients from a given discharging-well test will depend on the set of data collected in the field.

Distance-drawdown graph--This is a graph of the drawdown at a time t after the discharge begins, plotted against r on semi-logarithmic paper with r on the logarithmic scale. It may be thought of as a radial profile of the (logarithmic) cone of depression. Equating the quantity outside of the brackets in equation (3) with the slope of the graph, $2.303Q/2\pi T = \Delta s/\Delta\log_{10}r$ = slope of plot, whence $T = -(2.303Q/2\pi)(\Delta\log_{10}r/\Delta s)$. The negative sign indicates that s decreases as $\log_{10}r$ increases. For convenience, $\Delta\log_{10}r$ may be made unity by having it represent one logarithmic cycle, whereupon

$$T = -2.303Q/2\pi\Delta s \quad \ldots\ldots\ldots\ldots (6)$$

where Δs is the difference in drawdown over one logarithmic cycle.

Equating the second term in brackets in equation (3) with the intercept of the straight line on the zero-drawdown line, and solving for the coefficient of storage, gives equation (7).

$$S = 2.25Tt/r_0^2 \qquad (7)$$

where r_0 is the value of r at the s = 0-intercept.

Figure 1 is a distance-drawdown graph for wells that are 49, 100, and 150 feet from another well discharging at the rate of 2.23 cfs [test by S. W. LOHMAN reported by WENZEL, 1942]. The drawdowns at these distances after 18 days of continuous discharge were 5.09, 4.08, and 3.10 feet, respectively. The difference in drawdown over one logarithmic cycle is (0.69 ft - 4.07 ft) = - 3.38 ft. Therefore, from equation (6), T = 2.303(2.23 cfs)/(2 × 3.38 ft) = 0.242 cfs/ft.

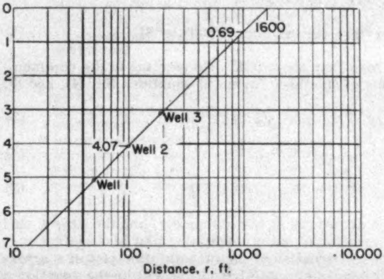

Fig. 1--Distance-drawdown graph based on drawdowns in three wells after 18 days of continuous discharge from an unconfined sand, Q = 2.23 cfs

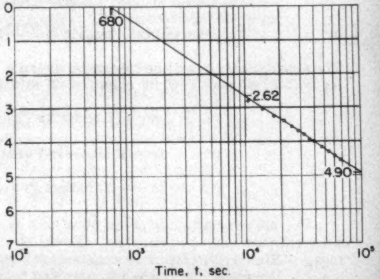

Fig. 2--Time-drawdown graph for a well 1200 feet from another well discharging from a confined sand, Q = 3.00 cfs

The straight line drawn through the plotted points intersects the zero-drawdown line at r_0 = 1600 ft. Thus, from equation (7), S = 2.25(0.242 cfs/ft)(18 days × 86,400 sec/day)/(1600 ft)^2 = 0.33.

Time-drawdown graph--This graph is a plot of the drawdowns in one of the observed wells against t on semi-logarithmic paper, with t on the logarithmic scale. The formulas for T and S are as in equations (8) and (9).

$$T = 2.303Q/4\pi\Delta s \qquad (8)$$

$$S = 2.25Tt_0/r^2 \qquad (9)$$

where t_0 is the value of t at the intercept.

Figure 2 is a time-drawdown graph for a well 1200 feet from another well discharging 3.00 cfs from a confined aquifer [JACOB, 1946]. The plotted points represent water-level readings from an automatic water-stage recording instrument, selected first at one-hour intervals and later at two-hour intervals. The change in drawdown over one logarithmic cycle is 2.28 feet. Accordingly, from equation (8), T = 2.303 (3.00 cfs)/(4π× 2.28 ft) = 0.241 cfs/ft.

The fact that this value for the coefficient of transmissibility agrees closely with that in the preceding example is fortuitous inasmuch as the two sets of data are from tests on different aquifers.

The intercept on the zero-drawdown line is t_0 = 680 seconds. Therefore, from equation (9), S = 2.25 (0.241 cfs/ft)(680 sec)/(1200 ft)^2 = 0.00026.

Composite drawdown graph--This graph is a plot of the drawdowns in several observed wells at different times against (r^2/t), on semi-logarithmic paper. The formulas for the coefficients of transmissibility and storage are as in equations (10) and (11).

$$T = -(2.303Q/4\pi)/\Delta s \quad \text{. . . . .} \quad (10)$$

$$S = 2.25T/(r^2/t)_0 \quad \text{. . . . .} \quad (11)$$

where $(r^2/t)_0$ is the value of (r^2/t) at the intercept.

Figure 3 is a composite drawdown graph that includes, in addition to the drawdowns in Figure 2, the drawdowns in a second idle well 1300 feet from the discharging well, and the drawdowns in the discharging well itself. The drawdowns in the discharging well are adjusted for an inferred screen loss of 28.5 feet [JACOB, 1946]. The discharging well is gravel-walled and its screen has a nominal diameter of 18 inches. The effective radius of the well is assumed to be 0.75 foot.

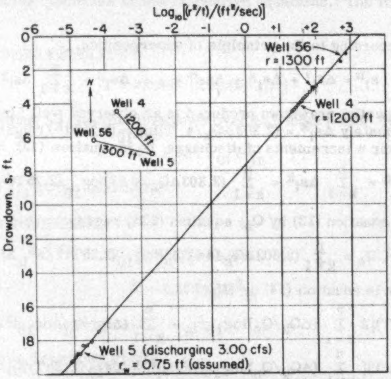

Fig. 3--Composite drawdown graph based on drawdowns observed in a discharging well and two neighboring wells in a confined sand (compare with Fig. 2)

The change in drawdown over one logarithmic cycle is -2.31 feet. This value substituted in equation (10) gives a coefficient of transmissibility of 0.238 cfs/ft. Inasmuch as the measurement of the discharge is correct only to two significant figures, this value does not differ significantly from that determined from Figure 2.

The intercept on the zero-drawdown line is $(r^2/t)_0$ = 2000 sq ft/sec. From this value, the coefficient of storage is computed to be 0.00027, which agrees closely with the value determined from Figure 2.

Generalized straight-line method

Before proceeding with the generalization of the straight-line method, it will be necessary to adopt a set of distinctive symbols to represent the various physical elements involved. The numerals 1, 2, 3, . . . will be used to identify the observed wells, and the letter i will be the general symbol for indicating any one of them. Thus, "Well i" will be understood to mean Well 1, Well 2, Well 3, etc., in turn. Other symbols are: ΔQ_k = increment of discharge for k = 1, 2, 3, 4, . . . n;

t^k = time elapsed since the inception of ΔQ_k for $t^k = t', t'', t''', t^{iv}, \ldots . t^n$; r_{ik} = distance from observed well i to the discharging well in which ΔQ_k occurred; $\Delta s_i{}^k$ = partial drawdown in observed well i produced by the increment of discharge ΔQ_k at the time t^k;

$$Q_n = \Delta Q_1 + \Delta Q_2 + \Delta Q_3 + \ldots \Delta Q_n = \sum_{k=1}^{n} \Delta Q_k$$

which is the algebraic sum of increments of discharge ΔQ_1 to ΔQ_n; and $s_i{}^n$ = total drawdown in observed well i produced by increments of discharge ΔQ_1 to ΔQ_n.

An increment of discharge ΔQ_k may be the initial discharge or a subsequent increase or decrease in discharge in any one of the discharging wells. Increases in discharge will be positive increments, and decreases will be negative. It will be convenient to assign numerals to k in chronological order, but where two or more increments of discharge occur simultaneously, the numerals may be assigned arbitrarily.

In the treatment of problems involving multiple discharging wells, or changes in the discharge of a single well, use is made of the principle of superposition, whereby it is assumed that the total drawdown produced in a given well at a given time by several increments of discharge is the algebraic sum of the drawdowns that would be produced independently by those increments of discharge. So far, the results of discharging-well tests have verified this assumption for artesian conditions.

Equation (12) is according to the principle of superposition.

$$s_i{}^n = \Delta s_i{}' + \Delta s_i{}'' + \Delta s_i{}''' + \ldots \Delta s_i{}^n = \sum_{k=1}^{n} \Delta s_i{}^k \quad \ldots\ldots\ldots\ldots (12)$$

From equation (2) the partial drawdown produced in an observed well i by an increment of discharge ΔQ_k is approximately $\Delta s_i{}^k = (2.303 \Delta Q_k/4 \ T) \log_{10}(2.25Tt^k/r^2{}_{ik}S)$, and from equation (12) the total drawdown, after n increments of discharge, is in equation (13), for n = 1, 2, 3, etc.

$$s_i{}^n = \sum_{k=1}^{n} \Delta s_i{}^k = \sum_{k=1}^{n} (2.303\Delta Q_k/4\pi T)\log_{10}(2.25Tt^k/r^2{}_{ik}S) \quad \ldots\ldots\ldots (13)$$

Dividing both sides of equation (13) by Q_n, equation (13a) results

$$s_i{}^n/Q_n = \sum_{k=1}^{n} (2.303\Delta Q_k/4\pi TQ_n)\log_{10}(2.25Tt^k/r^2{}_{ik}S) \quad \ldots\ldots\ldots\ldots (13a)$$

This may be written as in equation (14) or (15)

$$(s/Q)_i{}^n = -(2.30/4\pi T)[2 \sum_{k=1}^{n} (\Delta Q_k/Q_n)\log_{10} r_{ik} - \sum_{k=1}^{n} (\Delta Q_k/Q_n)\log_{10} t^k - \log_{10}(2.25T/S)] \ldots (14)$$

$$(s/Q)_i{}^n = -(2.30/4\pi T)[\sum_{k=1}^{n} (\Delta Q_k/Q_n)\log_{10}(r^2/t)_i{}^k - \log_{10}(2.25T/S)] \quad \ldots\ldots\ldots\ldots (15)$$

The first and second terms in brackets in equation (14) and the first term in brackets in equation (15) are the logarithms of the weighted logarithmic means of r^2, t, and (r^2/t) respectively. The weighted logarithmic means may be represented by $\overline{r}_{in}$, $\overline{t}^n$, and $\overline{(r^2/t)}_i{}^n$. Substituting these symbols in equations (14) and (15), we may now write the three equations (16), (17), and (18).

$$(s/Q)_i{}^n = -(2.303/2\pi T)[\log_{10}\overline{r}_{in} - (1/2)\log_{10}(2.25T\overline{t}^n/S)] \quad \ldots\ldots\ldots\ldots (16)$$

$$(s/Q)_i{}^n = (2.303/4\pi T)[\log_{10}\overline{t}^n - \log_{10}(\overline{r}^2{}_{in}S/2.25T)] \quad \ldots\ldots\ldots\ldots (17)$$

$$(s/Q)_i{}^n = -(2.303/4\pi T)[\log_{10}\overline{(r^2/t)}_i{}^n - \log_{10}(2.25T/S)] \quad \ldots\ldots\ldots\ldots (18)$$

These equations correspond with equations (3), (4), and (5) for single discharging wells, but include in addition to $\overline{s}_i{}^n$, $\overline{r}_{in}$, and $\overline{t}^n$, a fourth variable, Q_n. So that equations (16), (17), and (18) will be the equations of straight-line plots, Q_n has been combined with $s_i{}^n$ into a single variable $(s/Q)_i{}^n$, which may be referred to as the "specific drawdown" (drawdown per unit discharge). Thus, (16), (17), and (18) are the equations of the straight-line plots of the specific drawdown against $\overline{r}_{in}$, $\overline{t}^n$, and $(r^2/t)_i{}^n$, respectively, where $\overline{t}^n$ is constant in equation (16), $\overline{r}_{in}$ is constant in equation (17), and $\overline{r}_{in}$ and $\overline{t}^n$ are combined into a single variable in equation (18). As in equations (3), (4), and (5), the slope of each plot is represented by the quantity on the outside of the brackets in the corresponding equation, and the intercept of the extension of the plot at $(s/Q)_i{}^n = 0$ is represented by the second term within the brackets.

The weighted logarithmic mean distance $\bar{r}_{in}$ for a given observed well at a given time may be computed in the following manner: (1) Multiply each increment of discharge that occurred before the given time by the logarithm of the distance from the observed well to the well in which the increment occurred; (2) sum the products algebraically; (3) divide the sum of the products by the algebraic sum of the increments of discharge; and (4) extract the antilogarithm of the quotient. The result will be the distance $\bar{r}_{in}$. The weighted logarithmic means $\overline{t^n}$ and $\overline{(r^2/t)}_i{}^n$ are computed in a similar manner, but where $\bar{r}_{in}$ and $\overline{t^n}$ are already computed, $\overline{(r2/t)}_i{}^n$ may be obtained more conveniently by dividing $\bar{r}^2{}_{in}$ by $\overline{t^n}$ directly.

The weighted logarithmic means $\bar{r}_{in}$ and $\overline{t^n}$ both have physical significance. From a comparison of equation (16) with equation (3) it is evident that $\bar{r}_{in}$ is the distance at which a single well discharging at a rate Q_n would produce the drawdown $s_i{}^n$ at the elapsed time $\overline{t^n}$ after the discharge began. A recognition of the significance of these quantities is helpful in interpreting the plots.

The three types of graphs corresponding, respectively, to equations (16), (17), and (18) are referred to as the generalized distance-drawdown graph, the generalized time-drawdown graph, and the generalized composite drawdown graph. The formulas for determining the coefficients of transmissibility and storage from these graphs may be derived in the same manner as in the method for a single well discharging uniformly; that is, by equating the slopes and the intercepts of the plats with the corresponding quantities in the respective equations. The formulas are as in the following paragraphs.

Generalized distance-drawdown graph

$$T = -2.303/[2\pi\Delta(s/Q)_i{}^n] \tag{19}$$

where $\Delta(s/Q)_i{}^n$ is the change in specific drawdown over one logarithmic cycle.

$$S = 2.25T\,\bar{t}_0/\bar{r}^2{}_{in} \tag{20}$$

where $\bar{r}_0$ is the value of $\bar{r}_{in}$ at the intercept.

Generalized time-drawdown graph

$$T = 2.303/[4\pi\Delta(s/Q)_i{}^n] \tag{21}$$

$$S = 2.25T\bar{t}_0/\bar{r}^2{}_{in} \tag{22}$$

where $\bar{t}_0$ is the value of $\overline{t^n}$ at the intercept.

Generalized composite drawdown graph

$$T = -2.303/[4\pi\Delta(s/Q_i)^n] \tag{23}$$

$$S = 2.25T/\overline{(r^2/t)}_0 \tag{24}$$

where $\overline{(r^2/t)}_0$ is the value of $\overline{(r^2/t)}_i{}^n$ at the intercept. The use of the generalized composite drawdown graph is demonstrated in the example that follows.

Figure 4(a) shows the locations of wells at the Central Plant of the municipal water supply of Houston, Texas [GUYTON and ROSE, 1945]. The columnar sections, based on well logs, show by stippling the sands penetrated by the wells. The positions of the well screens are also indicated.

Figure 4(b) is a graph of the drawdown and subsequent partial recovery observed in Well F5 on October 10, 1939 [JACOB, 1941]. Well F10, 850 feet from Well F5, began pumping 2.27 cfs at 10^h00^m and stopped pumping at 18^h45^m. Well F1, 780 feet away, began pumping 2.79 cfs at 10^h30^m and stopped pumping at 20^h05^m. Well F12, 1060 feet away, began pumping 3.56 cfs at 11^h00^m and continued pumping through the end of the test. Measurements of the water level in Well F5 were made throughout the day. Some of these measurements, expressed as drawdowns, are platted in Figure 4(b), where the measurements used in applying the generalized straight-line graphical method are plotted each as two concentric circles.

Computations to determine values of the weighted logarithmic mean $\overline{(r^2/t)}^n$ and the corresponding values of the specific drawdown $(s/Q)^n$ are given in Table 1. (The subscript i, which refers to

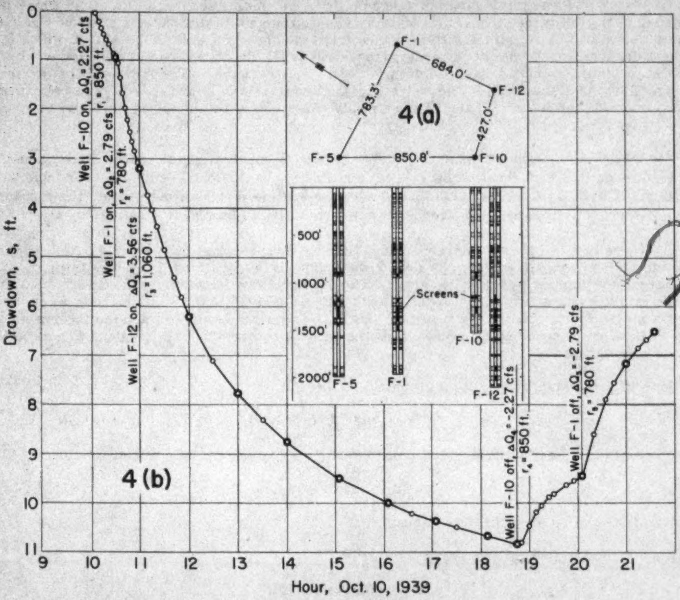

Fig. 4--(a) Map showing relative location of wells at Central Plant, Houston, Texas, and columnar sections based on well logs (after GUYTON and ROSE)
(b) Drawdown and subsequent partial recovery observed in Well F5, October 10, 1939, resulting from staggered operation of wells F10, F1, and F12

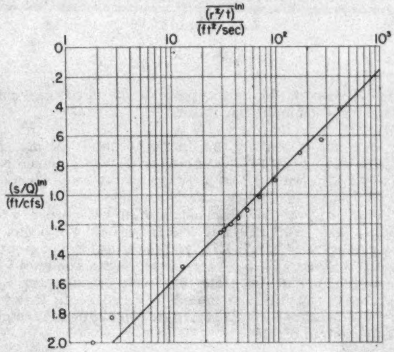

Fig. 5--Generalized composite drawdown graph for Well F5, Central Plant, Houston, Texas, October 10, 1939

Table 1--Computations of specific drawdown and weighted logarithmic mean $\overline{(r^2/t)}^n$ for Well F5, Central Plant, Houston, Texas, October 10, 1939

Time (1)	k (2)	n (3)	Discharge well (4)	r_k (5)	t^k (6)	(r^2_k/t^k) (7)	$Log_{10} (r^2_k/t^k)$ (8)	ΔQ_k (9)	(9)×(8) (10)	$Log_{10} (r^2/t)^n$ (11)	$\overline{(r^2/t)}^n$ (12)	s^n (13)	$(s/Q)^n$ (14)
h m				ft	sec	ft²/sec	ft²/sec	cfs	cfs		ft²/sec	ft	ft/cfs
10 30	1	1	F10	850	1800	402	2.604	2.27	....	2.604	402	0.96	0.423
11 00	1	..	F10	850	3600	201	2.303	2.27	5.23	....	....	...	....
	2	..	F1	780	1800	338	2.529	2.79	7.06	....	....	...	....
		2	...	...	...	...	....	5.06	12.29	2.429	269	3.20	0.632
12 00	1	..	F10	850	7200	100.4	2.002	2.27	4.54	....	....	...	....
	2	..	F1	780	5400	112.6	2.052	2.79	5.73	....	....	...	....
	3	..	F12	1060	3600	312	2.494	3.56	8.88	....	....	...	....
		3	...	...	...	...	....	8.62	19.15	2.222	167	6.21	0.720
13 00	1	..	F10	850	10800	66.9	1.826	2.27	4.15	....	....	...	....
	2	..	F1	780	9000	67.6	1.830	2.79	5.11	....	....	...	....
	3	..	F12	1060	7200	156	2.194	3.56	7.81	....	....	...	....
		3	...	...	...	...	....	8.62	17.07	1.980	95.5	7.77	0.901
14 00	1	..	F10	850	14400	50.2	1.701	2.27	3.86	....	....	...	....
	2	..	F1	780	12600	48.3	1.684	2.79	4.70	....	....	...	....
	3	..	F12	1060	10800	104	2.017	3.56	7.18	....	....	...	....
		3	...	...	...	...	....	8.62	15.74	1.826	67.0	8.76	1.016
15 05	1	..	F10	850	18300	39.5	1.597	2.27	3.63	....	....	...	....
	2	..	F1	780	16500	36.9	1.567	2.79	4.37	....	....	...	....
	3	..	F12	1060	14700	76.4	1.883	3.56	6.70	....	....	...	....
		3	...	...	...	...	....	8.62	14.70	1.705	50.7	9.50	1.102
16 05	1	..	F10	850	21900	33.0	1.518	2.27	3.45	....	....	...	....
	2	..	F1	780	20100	30.3	1.481	2.79	4.13	....	....	...	....
	3	..	F12	1060	18300	61.4	1.788	3.56	6.37	....	....	...	....
		3	...	...	...	...	....	8.62	3.95	1.618	41.5	10.00	1.160
17 05	1	..	F10	850	25500	28.3	1.453	2.27	3.30	....	....	...	....
	2	..	F1	780	23700	25.7	1.410	2.79	3.93	....	....	...	....
	3	..	F12	1060	21900	51.3	1.710	3.56	6.09	....	....	...	....
		3	...	...	...	...	....	8.62	13.32	1.545	35.1	10.37	1.203
18 08	1	..	F10	850	29280	24.7	1.392	2.27	3.160	....	....	...	....
	2	..	F1	780	27480	22.1	1.345	2.79	3.753	....	....	...	....
	3	..	F12	1060	25680	43.8	1.641	3.56	5.842	....	....	...	....
		3	...	...	...	...	....	8.62	12.755	1.4797	30.18	10.67	1.238
18 45	1	..	F10	850	31500	22.9	1.361	2.27	3.089	....	....	...	....
	2	..	F1	780	29700	20.5	1.311	2.79	3.658	....	....	...	....
	3	..	F12	1060	27900	40.3	1.605	3.56	5.714	....	....	...	....
		3	...	...	...	...	....	8.62	12.461	1.4456	27.90	10.84	1.258
20 05	1	..	F10	850	36300	19.9	1.299	2.27	2.949	....	....	...	....
	2	..	F1	780	34500	17.6	1.246	2.79	3.476	....	....	...	....
	3	..	F12	1060	32700	34.4	1.536	3.56	5.468	....	....	...	....
	4	..	F10	850	4800	150.5	2.177	-2.27	- 4.942	....	....	...	....
		4	...	...	...	...	....	6.35	6.951	1.0946	12.43	9.45	1.488
21 00	1	..	F10	850	39600	18.2	1.261	2.27	2.862	....	....	...	....
	2	..	F1	780	37800	16.1	1.207	2.79	3.368	....	....	...	....
	3	..	F12	1060	36000	31.2	1.494	3.56	5.319	....	....	...	....
	4	..	F10	850	8100	89.2	1.950	-2.27	- 4.427	....	....	...	....
	5	..	F1	780	3300	184.4	2.266	-2.79	- 6.322	....	....	...	....
		5	...	...	...	...	....	3.56	0.800	0.2247	1.678	7.16	2.011
21 35	1	..	F10	850	41700	17.3	1.239	2.27	2.813	....	....	...	....
	2	..	F1	780	39900	15.2	1.183	2.79	3.301	....	....	...	....
	3	..	F12	1060	38100	29.5	1.470	3.56	5.233	....	....	...	....
	4	..	F10	850	10200	70.8	1.850	-2.27	- 4.199	....	....	...	....
	5	..	F1	780	5400	112.7	2.052	-2.79	- 5.725	....	....	...	....
		5	...	...	...	...	....	3.56	1.423	0.3997	2.51	6.51	1.829

Note: The subscript i, which refers to the observation well, is omitted, because only one observation well is involved in the example.

the observation well, is omitted from the symbols because only one observation well is involved in the example.) The computation procedure may be observed by following the headings of the columns in the Table. The increments of discharge that occurred before the time given in column (1) are listed and summed algebraically in column (9). These increments of discharge are multiplied by the logarithms of the corresponding values of (r^2/t), and the products are listed and summed algebraically in column (10). The sum of the products given in column (10) is then divided by the sum of the increments of discharge given in column (9), and the quotient is listed in column (11). The antilogarithm of this quotient, listed in column (12) is the weighted logarithmic mean $(r^2/t)^n$. The corresponding value of the specific drawdown $(s/Q)^n$ is listed in column (14).

The data given in columns (12) and (14) are plotted in Figure 5. The alignment of the plotted points is not bad in view of the fact that the screens of the four wells are set at various depths and also the fact that the water-bearing sands are lenticular and vary in thickness and permeability from one well to another. The extent to which these or other circumstances might vitiate the method used may be judged most readily from the alignment of the points on a simple, straight-line graph such as Figure 5.

The change in specific drawdown $\Delta(s/Q)^n$ over one logarithmic cycle is -0.71 ft per cfs. Therefore, from equation (23) $T = 2.303/(4\pi \times 0.71$ ft/cfs $= 0.26$ cfs/ft.

The extension of the straight line in Figure 5 intersects the line of zero drawdown at $\overline{(r^2/t)^n} = \overline{(r^2/t)}_0^n = 1650$ ft^2/sec. Thus, from equation (24) $S = 2.25(0.26$ cfs/ft$)/(1650$ ft^2/sec$) = 0.00035$.

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TWO INTENSE LOCAL FLOODS IN NEW MEXICO

Luna B. Leopold

Owing to the paucity of data concerning the areal pattern of local storms in the southwestern United States, even relatively meager information becomes of some value. Only at the Mexican Springs Experiment Station near Gallup, New Mexico, is there a sufficiently close network of raingages to provide adequate data of this type [see HARROLD and DICKSON 1944, of "References" at end of paper]. There are other smaller experimental watersheds maintained by the Soil Conservation Service and the Forest Service where gages will help provide such data, but even in those areas general field observations in the surrounding locality usually are necessary to provide a reasonably complete estimate of the depth-area pattern of local storms [LEOPOLD, 1942].

There is a need, therefore, of additional descriptions of local storms such as the two discussed here, despite the fact that the significance of such data is seriously reduced owing to the lack of measurements of rainfall at the storm centers.

Storm of June 10, 1914, near Hillsboro, New Mexico--A storm of high intensity occurred the night of June 10, 1914, at the headwaters of Trujillo and Percha Arroyos near Hillsboro, New Mexico. Striking evidence of the flood was still plainly visible in 1939, 25 years after the storm. Logs of large walnut trees uprooted by the flow were left high above the normal channel and boulders a cubic yard in volume were rolled along grades of 1.0 to 1.2 per cent [Soil Conservation Service, 1939]. Amounts of rainfall at surrounding stations are shown on Figure 1 and Table 1.

Table 1--Rainfall, June 10, 1914

Station	Rainfall	Remarks
	in	
Hermosa	1.30	Between 20h00m and 23h45m MST
Lake Valley	1.05	Between 21h00m and 23h30m
Diamond Ranch	1.48	During night
Mimbres	1.65	During June 10
Pinos Altos	1.18	During night
Ft. Bayard	0.10	Between 18h30m and 20h00m
Fluorine	0.14	
Glorieta Ranch	0.02	

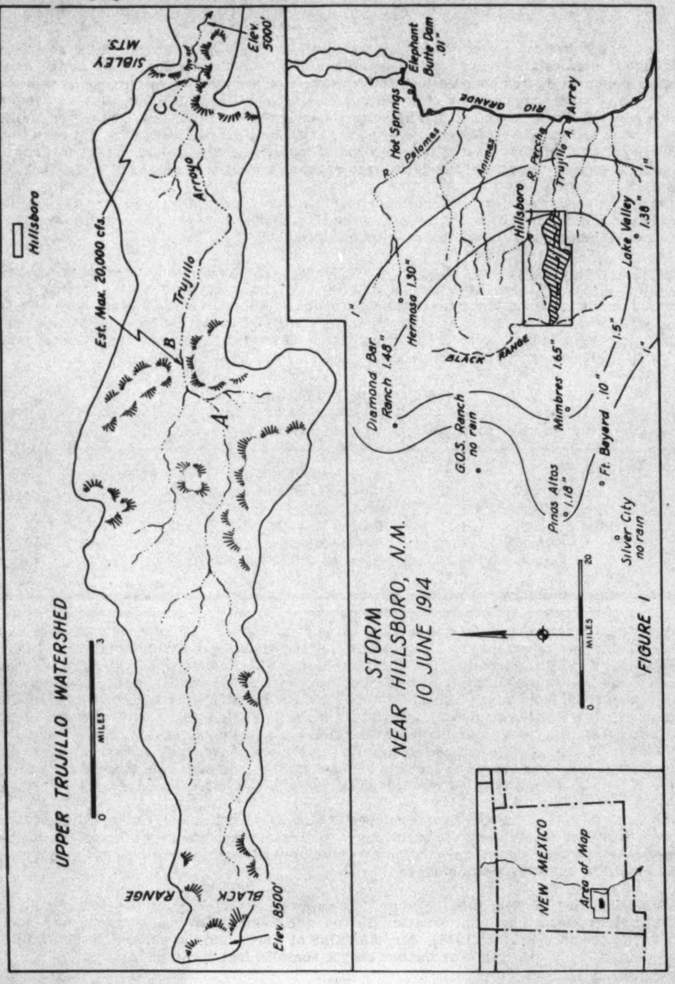
According to the Weather Bureau account "it is probable . . . . that a much greater amount (than was measured by existing raingages) fell over the divide between Hillsboro and Mimbres at the headwater of the Rio Perches" [U.S. Weather Bureau 1914]. This is corroborated by field evidence of the flow in the normally dry washes. The flood in the Trujillo left high-water marks still visible in 1939, from which a peak-flow of 20,000 cfs from 22 square miles was estimated at Trujillo Park, 3-1/2 miles southwest of Hillsboro (point B in Figures 1 and 5). An equal flow was estimated downstream, just above the box in the Sibley Mountains (31 square miles, point C in Figures 1 and 5). Large logs jammed by this flow in the box canyon can be seen in Figure 2. Water abrasion to a height of seven feet can be noted on the upstream side of the walnut tree shown in Figure 3. Location of the photograph is shown by the letter A on Figure 1.

The watershed on which this flow developed is mountainous and the average gradient of the channel is three per cent. The soils in the upper watershed are brown to light brown and contain lime. The vegetation is piñon juniper association except for grassland in the valleys and Ponderosa pine association in the highest mountain areas.

The flood in the Rio Percha at the same time swept as a wall of water six feet deep through the town of Hillsboro, according to the Weather Bureau, and, owing to advance warning, only one life was lost [U.S. Weather Bureau, 1914]. Mr. NATIONS of Arrey told the writer that Mr. MURPHY'S body was found "hung in a tree near the box canyon some 50 feet out of the channel."

The available evidence allowed a rough estimate of the area of the storm. Approximately 600 sq. mi. received 1.5 inches or more, 1300 sq. mi. 1.0 inches or more. The center of the storm would have been 36 sq. mi. had it covered the watersheds of the upper Trujillo and Percha above the points where the peak discharges were estimated.

Only 24-hour (Northern Hemisphere) surface synoptic maps were available to study this storm. The local storm evidently was associated with flow of mT air from the south toward a weak wave developing in northern Colorado.


UPPER TRUJILLO WATERSHED
0
MILES
3
SIBLEY MTS.
Elev. 5000'
C
Arroyo
Hillsboro
Est. Max. 20,000 cfs.
Trujillo
B
A
BLACK RANGE
Elev. 8500'
Elephant Butte Dam .01"
Hot Springs
RIO GRANDE
R.
Palomas
Animas
R. Percha
Trujillo A.
Arrey
Hillsboro
1"
Lake Valley 1.38"
Hermosa 1.30"
1"
Diamond Bar Ranch 1.48"
BLACK RANGE
Mimbres 1.65"
1.5"
.10"
1"
G.O.S. Ranch no rain
Ft. Bayard
Pinos Altos 1.18"
Silver City no rain
0
MILES
20
NEW MEXICO
Area of Map

STORM NEAR HILLSBORO, N.M. 10 JUNE 1914

FIGURE 1

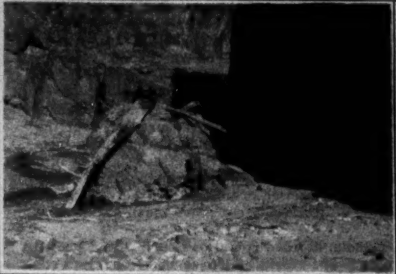


Fig. 2--Log jam caused by flood of June 1914 in Sibley Mt. box of Trujillo Arroyo, N. M.

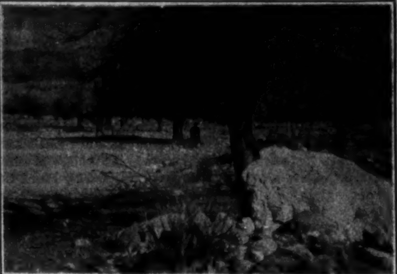
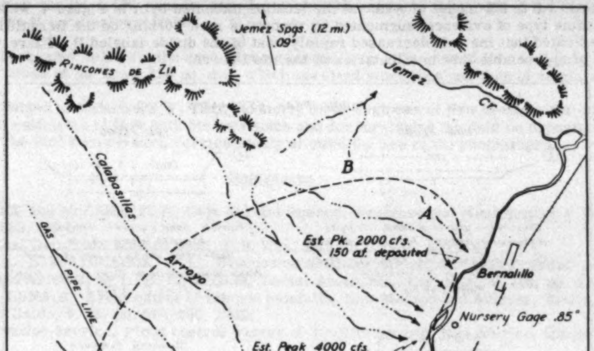


Fig. 3--Water abrasion on walnut tree in wide channel of Trujillo Arroyo, N. M.


Jemez Spgs. (12 mi.)
.09"
RINCONES DE ZIA
Jemez Cr.
B
Calabasillas
Arroyo
A
Est. Pk. 2000 cfs.
150 a.f. deposited
Bernalillo
GAS PIPE-LINE
Nursery Gage .85"
Est. Peak 4000 cfs.
150 a.f. deposited in fan
D
Sandia
C
RIO GRANDE
Est. Peak 10,000 cfs.
250 a.f. deposited in fan
1"
A.T. & S.F. RR.
0 MILES 5
No Rain
Albuquerque
Trace
Area of Map
NEW MEXICO

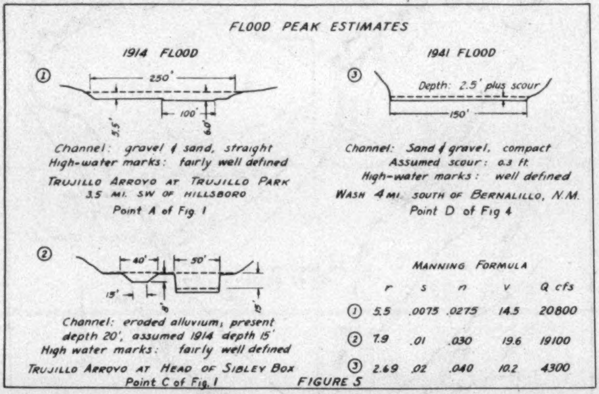
STORM
NEAR ALBUQUERQUE, N.M.
20 SEPT. 1941

FIGURE 4

Storm of September 20, 1941, near Albuquerque, New Mexico--Between 14^h00^m and 17^h00^m MST, September 20, 1941, a severe thunderstorm occurred a few miles northwest of the city of Albuquerque, New Mexico. The center of the storm moved northeastward over the Llano de Albuquerque, a broad mesa separating the Rio Grande from the Rio Puerco Watershed to the west.

During the two days prior to September 20 there was a flow of mT air west from the Gulf of Mexico and then northward into New Mexico under the influence of a high-pressure cell over the northeastern States. At the time of the local storm near Albuquerque a cold front extended from Phoenix to Denver, then northward through Minnesota. The cold front strengthened the flow of mT air into New Mexico and was preceded by local thunderstorms scattered over the State. The radiosonde record of Albuquerque at 09^h00^m LST September 20, showed prominent convective instability and relative humidities over 85 per cent at most levels up to 17,000 feet above mean sea-level.

A field investigation was made September 23, as soon as road conditions permitted. The only raingages in the area were located near the perimeter of the storm. Albuquerque No. 1 reported no rain eight miles southeast of the center of the storm. An intensity gage at the Soil Conservation Nursery south of Bernalillo was near the edge of the storm and recorded 0.69 inch in 30 minutes and a total of 0.85 inch in 110 minutes. Inspection of water collected in tin cans and other containers showed 1.5 to 2.5 inches of water at the location indicated by A in Figure 4, west of Bernalillo. The same type of evidence, augmented by reports of men working on the Bernalillo-Cuba Highway, indicated that the rain decreased rapidly west of the divide labeled B. There were no indications of appreciable flow in tributaries of the Rio Puerco.


FLOOD PEAK ESTIMATES
1914 FLOOD
①
250'
100'
5.5'
6.0'
Channel: gravel & sand, straight
High-water marks: fairly well defined
TRUJILLO ARROYO AT TRUJILLO PARK
3.5 MI. SW OF HILLSBORO
Point A of Fig. 1
1941 FLOOD
③
Depth: 2.5' plus scour
150'
Channel: Sand & gravel, compact
Assumed scour: 0.3 ft.
High-water marks: well defined
WASH 4 MI. SOUTH OF BERNALILLO, N.M.
Point D of Fig 4
②
40'
50'
15'
Channel: eroded alluvium; present
depth 20', assumed 1914 depth 15'
High water marks: fairly well defined
TRUJILLO ARROYO AT HEAD OF SIBLEY BOX
Point C of Fig. 1
MANNING FORMULA

	r	s	n	v	Q cfs
①	5.5	.0075	.0275	14.5	20800
②	7.9	.01	.030	19.6	19100
③	2.69	.02	.040	10.2	4300

FIGURE 5

Totals of rainfall for the day showed that there were scattered storms in the State, but the stations closest to the center of this particular thunderstorm recorded the following:

Table 2--Totals of rainfall, September 20, 1941

Station	Rainfall
Los Lunas	None
San Fidel	0.20 inch
Laguna	None
Albuquerque No. 1	None
Bernalillo	0.85 inch
Jemez Springs	0.09 inch
Lee Ranch	None

Although no large amounts of rain were recorded by gages, the flash flows in the ephemeral washes draining the mesa indicated an exceptional rainfall. High-water marks and the character of the channels and material deposited allowed a rough estimate of the peak flows. At the mouth of Calabasillas Arroyo (see Fig. 4) the peak must have been of the order of 10,000 cfs contributed from only a portion of the total drainage area of 85 sq. mi. A primary gas main feeding the city of Albuquerque was washed out by a tributary of this arroyo at a point indicated by C on Figure 4.

Local testimony indicated that a similar flash flow occurred in Calabasillas Arroyo in 1904.

Estimates of the peak flow of other arroyos are shown in Figure 4. The area on which these discharges originated is a mesa whose top slopes southeast at an average rate of 22 feet per mile. The soil is sandy loam and the upper 20 feet of the old pediment surface consists of poorly consolidated gravels and sands containing considerable amounts of caliche [Soil Conservation Service, 1939].

At the mouth of Calabasillas Arroyo an estimated 250 acre-feet of sediment, primarily sand, were deposited as a fan which forced the flow of the Rio Grande into a narrow channel against the east bank of the main flood plain. The total contribution of sediment must have been even larger because much was carried downstream by the combined flow of the arroyo and the Rio Grande. The depth of deposition was nine feet in places. Some large boulders were deposited in the fan. One, estimated weight 1,400 pounds, was deposited 700 feet from the mouth of the arroyo and five feet above the normal streambed.

The data roughly delineate the area of most intense rain. The dotted line in Figure 4 is the writer's estimate of the area, 110 sq. mi., which received more than one inch of rainfall.

I am indebted to HERBERT W. YEO, formerly State Engineer of New Mexico, for checking my field estimates of flow with his own notes and for furnishing the data on deposition of sediment. The Soil Conservation Service kindly allowed the use of the photographs.

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Los Angeles, California

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LAMINAR FLOW IN THE HONOLULU AQUIFER

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Abstract--It has commonly been found that the flow of ground water through natural aquifers is laminar, with discharge in linear proportion to hydraulic slope. High permeability of the Honolulu aquifer and the large amounts of water derived from it in single wells have led engineers and others to consider whether some of the flow might not be turbulent. In earlier studies, distinction was not made between head loss very close to the well and that at greater distances, with the result that turbulent flow in the aquifer was thought to exist, and values of the velocity exponent, N, were calculated as distinctive of particular parts of the aquifer. The present study shows that turbulent flow is found within the first few feet of large wells at large rates of discharge, but that such flow is quite restricted, and that it is incorrect to deduce a value of N differing from unity as characteristic of the aquifer rock itself. The study shows that flow under all known natural conditions is laminar, thus with N equal to unity, and that all calculations of seaward or lateral leakage or transfer under natural head differences should be made on that assumption. Any deviations in the direction of turbulent flow are characteristics of the operating station or well at high discharges, and invade the rock only for very short distances.

Introduction--It is essential in hydraulic calculations to distinguish between turbulent and laminar flow. Despite the classic studies of OSBORNE REYNOLDS and the formulation of the REYNOLDS number as early as 1883 [REYNOLDS, 1883, see "References" at end of paper], the concept and use of the REYNOLDS number as a criterion to distinguish turbulent from laminar flow has only recently become well known among workers in applied hydraulics. Engineers concerned with flow of water through pipes and open channels have used formulas with empirical constants applicable through the range of turbulent flow, and geologists and other students of ground water have used DARCY'S law to calculate the flow of ground water, but neither group has given much attention to the transition between these two types of flow [POWELL, 1940].

The general formula relating head to quantity of flow through a pipe or similar opening is

$$H = K Q^N$$

where K is a constant depending on the shape and size of the opening, the density and viscosity of the liquid, and the acceleration of gravity. At relatively low velocities and in small openings, the rate of flow is directly proportional to the head and the exponent N is equal to one, a relationship generally known as DARCY'S law.

At higher velocities or through larger openings, or both, the rate of flow increases less rapidly than the head difference, and N becomes greater than 1 and may approach 2. Such flow is known as turbulent flow, and is determined dominantly by rate of mass movement; hence, the velocity at which change from one to the other takes place is in part a function of the respective viscosity and density of the liquid in question. The studies of REYNOLDS in 1883 led to a generalized formula including the viscosity and density of the liquid, the diameter of the opening, and the velocity, which for all fluids, furnishes a definition of this transition. This formula

$$R = \rho v D / \mu$$

where D is the diameter of the opening, v is velocity, ρ is density, and μ is viscosity, gives the value of the REYNOLDS number, R. It has been shown that when the value of R exceeds 2300, turbulent flow may be expected; with R less than 2300, turbulent flow cannot persist and the flow is laminar. With flow through porous sands, where diameters of openings cannot readily be determined, mean or representative diameter of grain may be substituted, or in the case of open channels, the hydraulic radius may be used, there being in either instance an appropriate modification of the numerical value 2300. In any event, with proper handling of the dimensions, the concept and mode of formal comparison represented by the REYNOLDS number for different conditions of flow is fundamental, and has proved increasingly useful, especially for studies of flow of various fluids, and in the design and interpretation of model studies.

Structure of the Honolulu aquifer--It has been rather generally shown that the ground-water flow in most regions of the Earth takes place at velocities and under conditions which favor laminar flow, in accordance with DARCY'S law [FISHEL, 1935; MEINZER and WENZEL, 1942; TOLMAN, 1937; MUSKAT, 1937; and WENZEL, 1942]. The Honolulu aquifer differs in some notable respects from the water-producing formations known in many regions, and some of its characteristics invite question as to whether ground water in it may not move at velocities within the range of turbulent flow. This question was particularly raised in connection with hydraulic tests of the Honolulu artesian system in 1934 and 1935 [HOYT, 1935].

The Honolulu aquifer consists of upward of 2000 feet of basaltic lava flows of the Koolau series. Both the ropey pahoehoe flows and the clinkery aa flows are present, but the latter make up probably 80 per cent of the thickness in the coastal and most-penetrated part of the aquifer. The prevailing thickness of individual flows is not over 10 or 15 feet; locally a few aa flows reach 30 to 50 feet in thickness. It must be emphasized that all aa flows have a dense interior, broken by cooling fractures, which is usually both overlain and underlain by irregular layers of detrital clinker developed in course of flowing down slope. It must further be pointed out that it is the main, interior, unweathered section of the lava flows making up the volcanic dome and probably extending some thousands of feet below sea level that constitutes the aquifer. Gravel and all other sediments in Hawaii are, in the main, much weathered, and in large masses form water barriers, not aquifers. All sediments in the Honolulu area, whether in valleys or on the coastal plain, are part of the cap rock rather than of the major aquifer.

The outstanding features of the Honolulu aquifer are the shapes and distribution of the fissure-like openings between the contraction blocks of lava flows, the irregularity and general openness of contact between adjacent lava flows, with or without porous and permeable clinker layers, the sporadic presence of large lava tubes which may reach widths of 30 or 40 feet and heights of 10 feet or more, and the very high general permeability shown by the specific yields of wells and pits. Moreover, this formation, saturated with fresh water, not only extends over a width of two to five miles inland from the coast and over ten miles lengthwise along the Honolulu coast, but so far as known also extends with comparable openness of texture to depths of at least 1000 and quite likely 1500 feet, or more, below sea level. It is enormously thicker than any gravel or other permeable sedimentary formation known to the writer. Such great extent in three dimensions makes it desirable to envisage a potential field of three dimensions, and makes mathematical treatment much more complicated than in a formation which is practically confined between impermeable top and bottom beds. Despite the lamination due to successive lava flows, evidence from the behavior of water near wells, pits, and tunnels does not clearly indicate that the ground water moves with greater ease parallel to the flows than across them. This is apart from the local influence of dikes and sills in some areas near the dike complex, which is irrelevant to the question in hand.

Method of approach in evaluating N--In any calculation of the rate of flow of water from known or assumed ground-water slopes or differences of head, it is essential to know whether the flow is according to DARCY'S law, where $N = 1$, or if it is partly turbulent flow under conditions where $N > 1$ and may approach the value of 2. Hence, in any hydraulic calculations where water-discharge rates are assumed to be some function of measured or assumed head differences, it is important, if possible, to determine or delimit the assumed value of N. In so doing it will be profitable to consider possible variations in the various factors contained in the formula for the REYNOLDS number. Of these, density and viscosity are substantially fixed in the present problem; velocity and diameter may vary. The chief unknowns in the shore part of the aquifer are the porosity, the thickness of the aquifer through which movement takes place, and the size and distribution of openings. The portion of the aquifer in which measurements of head are made and from which fresh water is drawn by artesian wells is certainly 500 feet thick--in most places twice this amount. Given the area of cross section, for a given rate of discharge the velocity is reciprocal to the percentage of porosity. Since increasing porosity may mean in part comparable increase in diameter of opening, the terms velocity and diameter in the formula would, in a given cross section with fixed discharge, tend to vary in a reciprocal manner and make only slight changes in the value of the REYNOLDS number.

The first and most general estimate we can make as to possible conditions of flow is that based on the velocity of flow through an assumed cross section calculated as adequate to discharge the amounts of water that are infiltrated daily in any given sector. The most convenient unit is the shore-line mile.

The total average rainfall on the Honolulu watershed for the ten shore-line miles from Diamond Head to Red Hill is about 214 mgd; the rainfall on the area tributary to the main aquifer as outlined through geologic studies is about 123 mgd. Basal infiltration has been estimated as about 40 mgd.

Estimates by another method suggest that somewhat over 90 mgd may reach the basal water body and be divided between draft and natural leakage. Without further discussion, we can plausibly take the figures 50 and 100 mgd as reasonable lower and upper limits to the rate of movement of water through the basal body. These figures represent five to ten mgd per shore-line mile. This amount moves through a prism one mile wide, whose thickness and porosity we may postulate within certain limits.

For a discharge of ten mgd per mile of width through an aquifer 500 feet thick, with porosity at ten per cent, the macroscopic velocity is five feet per day. (According to MUSKAT [1937, p. 67], the general rate of flow in artesian aquifers is one to three miles per year, or 14 to 43 feet per day.) A velocity of five feet per day corresponds to a REYNOLDS number of less than six in an opening of one-foot diameter, and about 55 in a ten-foot opening. Although these data are only presumptive, our information on the field conditions does not suggest that these values could be modified to cause the REYNOLDS number to approach 2300 except in the most special and restricted part of the aquifer adjacent to artificial draft.

Another approach can be made on the basis of known hydraulic gradients. These rarely exceed one foot or two feet to the mile in positions where they apply to the main shoreward movement. Such slopes in tubular openings of two-inch diameter could produce turbulent flow with a velocity of about four miles per day. However, if as much as 0.001 part of the water contained in the section at porosity of ten per cent were moving with such a velocity, the discharge would be about four times the maximum presumed rate of ten mgd per shore-line mile. It appears, therefore, that the nature of the openings and the permeability are such that the observed slopes are indeed necessary to discharge the amount postulated, and that if local combinations of velocity and size of opening inducing turbulent flow do occur, they must be so localized and so restricted by their demand for water quantities at their upper and lower ends that their effect on the functioning of the whole aquifer is negligible.

It is essential to distinguish between the conditions of flow occurring naturally and those developed by draft at wells, pits, or tunnels. It was emphasized above that the motion of water in the aquifer is controlled jointly by the geometry of the aquifer and by the steady as well as transitory hydraulic slopes that exist within the aquifer. It is not correct to envisage a value of N definitive of the aquifer itself; any value of N we can determine is here, as in pipes or other openings, a function of the conditions of flow within a specified range of both openings and velocities. Moreover, if in measurements made through a given segment of the aquifer, certain values of N are deduced, it should be recognized that these can certainly not be regarded as applicable to a portion of the aquifer in which conditions of flow differ materially from those in the test portion. As a criterion of the comparability of conditions of flow, the REYNOLDS number is of prime value, since in various types of model experiments on the flow of water, or the slow movement of submerged solids through water, direct comparison between model and prototype is found to be justifiable for sets of conditions which have the same ranges of REYNOLDS numbers, and not otherwise.

The probability of existence of large openings with great hydraulic slope for any considerable distance within the meshwork of smaller openings is reduced by the tendency of a stream tube of such capacity to form a sink in the hydraulic surface at the upper end and a source at the lower end, thus reducing the slope and at once tending to minimize the possibility of excessively high velocities.

For example, let us consider an opening of six inches in diameter 1000 feet in length at a general water-table slope of 0.005. Such a tube would discharge about 0.15 mgd and under the generally prevailing permeability of the Honolulu aquifer, the delivery of such a quantity of water into the upper end of the tube would require a drawdown of at least two or three feet, and the "build-up" in the potential surface at the other end would be of similar height. The two together would cancel the five feet of difference in head implied in the length and slope given. From such considerations, one reaches the conclusion that turbulent flow in stream tubes, which begin and end in the potential surface extending from the water table to the ocean level, and which are surrounded by rock of the permeability of the Honolulu aquifer, is essentially impossible. Although these various comparisons do not deny the possibility of movement of ground water in a few large openings locally by turbulent flow, they support the view that the greater part of the movement of water takes place by laminar flow, and that the extent of turbulent flow must be extremely limited.

Experimental tests of flow into wells--In 1934 there was started a series of tests to determine certain hydrologic characteristics and dimensions of the Honolulu ground-water system by mathematical analysis of data derived from arranged pumping schedules and measurements. At this time it was recognized that one of the important parameters required in various calculations is the exponent which defines the relationship between drawdown and discharge, and that for laminar (capillary) flow the value of the exponent would be unity, for flow through an opening of moderate size it would approximate 1.85 [HOYT, 1935]. It was suggested further that the relation between discharge and drawdown in wells of the artesian system should be "determined as being of some future use in estimating natural leakage" [HOYT, 1935, p. 150].

Accordingly, tests were made in 1934 of a number of individual wells and groups of wells at the several pump stations, to relate discharge and drawdown. The results of these tests are compiled in Table 1. The test runs were made under the general direction of J. F. KUNESH and much of the computation was either made or checked by him. In the case of the groups of wells at a given pump station, the pumps were run at three rates of discharge (about 4, 10, and 14 mgd at Beretania, for example), as measured by Venturi meters. The initial static head was measured on each well and the steady operating head was recorded by a gage tube attached alongside the well. The difference was considered as individual total drawdown. The remainder of the calculation was by groups. The average draft per well was taken as the total draft divided by the number of wells. The friction in the well casings was calculated by computing a weighted mean age for the wells and using the column in the WILLIAMS and HAZEN Hydraulic Tables most nearly corresponding to this number of years, without attempting to interpolate further. From the friction loss thus obtained per 1000 feet, the friction loss for the total combined length of casing was obtained, and to this was added a value for velocity head. This amount, subtracted from total combined drawdown for the wells, and divided by the number of wells, gave the net average aquifer drawdown per well. Where necessary, account was taken of different casing sizes in computing the weighted average and total pipe friction in the combined wells. Thus, referring to Figure 1, it appears that in these calculations the head loss, "A", occurring in the well casing, both velocity and frictional, was subtracted from the whole, leaving for the drawdown in the aquifer near the well, "B", and for that in the more remote part of the aquifer, "C."

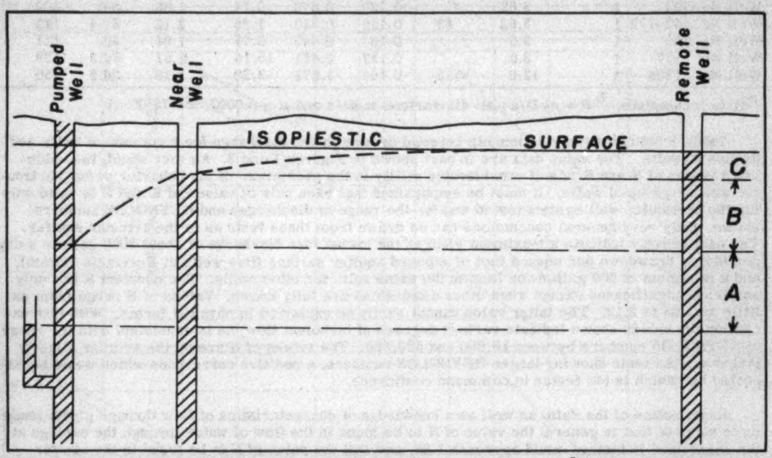

Fig. 1--Diagram showing components of total drawdown or loss of head [A is head loss in well casing; B is head loss in aquifer between surface of well being pumped and observation well at station; C is head loss between observation well and remote well which for short periods represents substantially undisturbed isopiestic level.]

The resulting mean net drawdown per well, H, for each rate of discharge, Q, was used in calculating the values K and N in the formula $H = KQ^N$. For most of the stations there were data for three values of Q, approximating 4, 10, and 14 mgd. For Kaimuki Station, values of approximately 4, 10, 12, and 14 mgd were used. Solutions were made by the usual least-squares procedure. Similar tests were run for a number of wells and results were similarly computed. The resulting values of K and N are shown in Table 1.

Table 1--Characteristics of flow into certain wells and stations

Unit	Number wells	Size well	Area of exposed aquifer	Range Q From	Range Q To	K	N	Range in 1000's REYNOLDS number[b] From	To
		inch	sq ft	mgd	mgd				
Beretania	5	12	2437	4	14	0.039	1.88	149	520
Beretania	8	six 12 two 9.62	3380	4	14	0.042	1.69	100	350
Kaimuki	7	12	4465[a]	4	14	0.043	1.48	107	374
Kalihi	7	five 12 two 11.62	3540[a]	4	14	0.070	1.57	108	377
Well No. 66	1	7.62	....	0.111	0.454	10.23	1.62	32.6	133
Well No. 5-1/2	1	9.62	330	0.144	1.30	5.92	1.11	33.5	302
Well No. 43	1	7.62	....	0.072	0.166	8.85	1.06	21	48.8
Well No. 50	1	9.62	....	0 072	0.346	5.69	1.42	16.7	80
Well No. 51	1	9.62	....	0.130	0.878	5.14	1.08	30	204
Well No. 52-1/2	1	5.62	63	0.130	0.310	1.85	2.12	51.4	122
Well No. 99	1	9.0	....	0.184	0.447	2.71	1.84	46.	111
Well No. 117	1	8.0	....	0.137	0.461	15.16	1.51	38.3	129
Well No. 120A	1	12.0	530	0.144	1.872	3.20	1.10	26.9	350

[a] Data incomplete. [b] $R = \rho v D/\mu$; all dimensions metric and $\mu = 0.0097$, for 72°F.

Table 1 indicates the relationship between drawdown and discharge for a number of wells and groups of wells. The same data are in part shown in Figures 1 and 2. As they stand, the calculated values of K and N are of considerable utility in the prediction of the behavior of any particular well or group of wells. It must be emphasized that each pair of values of K and N is valid only for the particular well system tested and for the range of discharges and REYNOLDS numbers shown. Only very general conclusions can be drawn from these tests as to the artesian aquifer. The data broadly indicate a maximum yield at the lowest test discharge of about 2000 gallons a day per foot of drawdown per square foot of exposed aquifer surface (five wells at Beretania Station), and a minimum of 500 gallons or less in the same units for other wells. The constant K has only empirical significance except when other dimensions are fully known. Values of N range from as little as 1.06 to 2.12. The latter value cannot easily be explained in physical terms. With this exception the values shown indicate various degrees of turbulent flow, as is consistent with the range of REYNOLDS numbers between 16,000 and 520,000. The values of N are on the average slightly larger for the tests showing larger REYNOLDS numbers, a positive correlation which would be expected but which is too feeble to command confidence.

Examination of the data, as well as a knowledge of characteristics of flow through pipes, leads us to suppose that in general the value of N to be found in the flow of water through the casings at the rates used in testing would approach 1.85, and that the value of N to be found in the aquifer zone immediately adjacent to the well would be greater than that found for zones progressively farther away from the well, but would probably be less than 1.85. This is to be expected, even in the case of a single tubular opening, if velocities and REYNOLDS numbers are reduced sufficiently and would even more be expected with the reduction of mean velocities in successive shells of permeable rock where openings of great variety of size and shape make up the entire permeability fabric. The values of N shown in Table 1 are based on total head loss (B+C) in the aquifer, so far as it could be determined, but exclude the head loss in the well casing. The greater part of the head loss in the aquifer is concentrated close to the well in the inner concentric shells. If the values of N are calculated separately for the portion close to the well and for the part more remote from the well, it is found that almost the entire detectable deviation from laminar flow is concentrated in the shells in the immediate vicinity of the well, and it is due almost wholly to this effect that the values originally computed for the various wells differ materially from unity (see Table 2 and Fig. 2).

Table 2--Values of N for different zones at three Honolulu stations

Station	Range Q From	Range Q To	Values of N: Drawdown B[a]	Drawdown (B+C)	Drawdown C[b]
	mgd	mgd			
Beretania (8 wells)	4.05	14.32	1.81	1.69	1.00
Kaimuki (7 wells)	4.00	14.06	1.67	1.48	1.00
Kalihi (7 wells)	4.00	14.00	1.68	1.57	1.00

[a] Head drop from observation well to active wells. [b] Head drop from undisturbed water table to observation well.

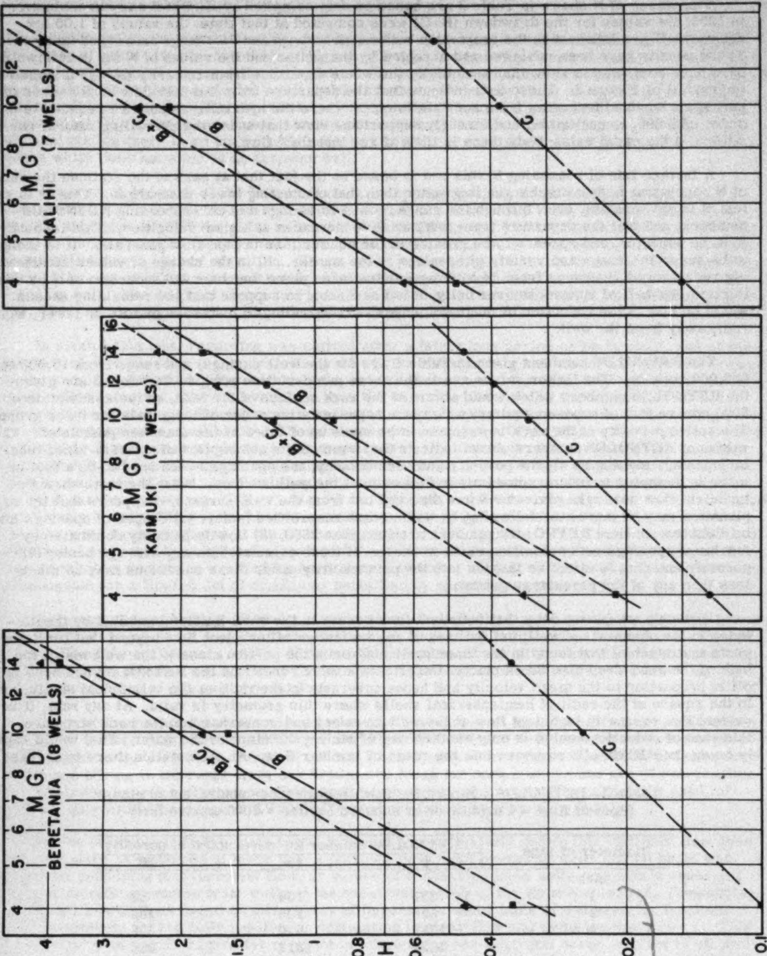

Fig. 2--Drawdown and discharge for Beretania, Kaimuki, and Kalihi artesian stations [Drawdown A, not shown, is head loss due to pipe friction in well casing; drawdown B is head loss between pumped well and observation well; drawdown C is loss in remoter part of aquifer--both as shown in Fig. 1. In each case, graphs are shown for drawdown (B + C), B, and C, respectively. Lines for C are at practically 1:1 slope, indicating N = 1. For B, the lines show values of N in excess of 1, as shown in Table 2. Values of (B + C) are dominated by those of B, and hence values of N are here also in excess of 1.]

The values of N shown in Table 2 are based on data compiled by KUNESH and his assistants in 1934; the values for the drawdown (B+C) were computed at that time; the values of 1.00 for drawdown C are inherent in the proportion between drawdown and discharge as worked up by them. These results have been reviewed and accepted by the writer and the values of N for drawdown B have been computed to show that essentially the whole departure from linearity (N = 1) is contained in graph B of Figure 2. These data indicate that the departure from laminar flow at distances of perhaps a hundred feet away from such stations, or where the hydraulic slopes are reduced to the order of 0.005, is negligible, and strongly support the view that under the prevailing natural conditions in the basal water body there is little if any turbulent flow.

A further line of reasoning to this end is based on the fact that at each of the stations the value of N connecting higher discharges is greater than that connecting lower discharges. This is to say that N is not constant, even through the range from 4 to 14 mgd and corresponding REYNOLDS numbers, and that the departure from laminar flow increases at higher velocities. This tendency is to be expected, and appears to be greater in the aquifer than in pipe flow generally. It is thought to be due to the range and variety of openings in the aquifer. If, in the change of velocities attending reduction of discharge from 14 to 4 mgd, there takes place the observed reduction of N by one-third to one-half of its excess over unity, it is reasonable to suppose that the remaining excess would be lost in the reduction of mean velocities corresponding to distances of 100, or fewer, well radii away from the well.

The REYNOLDS numbers given in Table 1 are for the well casings, and range from 15,000 to 500,000 roughly. The larger values are in the three pump-station groups. In Table 3 are given the REYNOLDS numbers which would obtain at the rock surface of the well, on the assumption of 3000 square feet of exposed aquifer, which is a representative order of magnitude for these groups. The entire porosity of the rock is assumed to be made up of tubes of the diameter postulated. The values of REYNOLDS numbers shown indicate that even on the assumption of uniform-sized tubular openings making up all the porosity and permeability, the openings would need to be a foot or more in diameter to induce non-laminar flow even at the well surface. Since the tests show that turbulent flow does take place for some distance out from the well surface, it appears that the explanation may be one of the following, or some other unspecified factor; (1) Shapes of openings may be such that critical REYNOLDS numbers are less than 2300; (2) flow is possibly dominated by a few large openings with velocities much in excess of those calculated on any average basis; (3) porosity entering in effective fashion into the permeability under these conditions may be much less than any of the percentages shown.

Obviously we cannot deny that turbulent flow occurs in the shell limited in radius by the distance to the observation well, but the lack of any indication of turbulent flow beyond that limit suggests that much of that found in the inner shell may be in the portion close to the well where the bulk of the head drop also takes place. Under comparable conditions the REYNOLDS numbers fall off in proportion to the mean velocity and hence inversely to the radii of the cylindrical shells, or to the square of the radii of hemispherical shells where this geometry is valid. At any rate, it is evident that even with turbulent flow at the well boundary and somewhat into the rock structure, this rate of reduction (which is only another way of stating the slope of the water table) would rapidly bring the REYNOLDS numbers into the range of laminar flow. At each station there is at least one pumped well within about 50 feet of the observation well, and the average distances are around 100 feet. However, the preponderant effect is that of the nearer wells, and a weighted mean computed on this basis, shows values that center at somewhat under 100 feet. From the fact that all the demonstrable turbulent flow is contained within a shell of radius less than 100 feet, it appears probable that extremely little turbulent flow would be found outside a radius of even 25 feet, if we

Table 3--REYNOLDS numbers for flow through tubes equivalent to pipes
(Rate of flow = 4 mgd; area of exposed aquifer = 3000 square feet)

Diameter of pipe	REYNOLDS number for percentage of porosity		
	5	10	20
inch			
1	328	164	82
2	656	328	164
4	1312	656	328
8	2624	1312	656
16	5250	2624	1312

had observation points to make the test.

Supplementing the conclusions reached by review of these early tests of artesian wells, certain tests of basal stations have been analyzed. Despite the fact that in certain respects the conditions of such tests are more difficult to define, the general conclusions are similar. Unfortunately, at no station do we have a single, properly placed observation hole close enough to give a readily measured drawdown for different rates and remote enough from the sump to avoid the possibility of turbulent flow already mentioned. Another drawback is the fact that in a sump-and-tunnel type of basal station there is an unavoidable reduction of area of rock surface due to drawdown, a condition which does not exist in an artesian well.

However, in the case of the Halawa Station, completed in 1944, these drawbacks are happily minimized. First, the yield from the sump is a small fraction of the total, less than ten per cent. Second, the upper part of the sump is in rock of particularly low yield. The chief yield in the Halawa Station is from the more remote part of the tunnel, all of which remains submerged until the sump falls below a 12-foot elevation. Hence, up to rather large discharge and drawdown, there is very little loss of inflow area and the drawdown-discharge diagram is very much like that of an artesian well. The diagram shown in Figure 3 is based on a test at the end of construction in January, 1944, as already reported [Board of Water Supply, 1945].

In making this test, recording was started after a fairly long period of heavy draft, and at the moment of shutting down the pumps. The rate of rise of water was measured, and from the volume of the sump and tunnel at different levels the so-called rate with rise (Fig. 3, graph AB) was calculated. This rate is at various levels less than the true rate of inflow by the unknown amount absorbed by rock storage. Subsequently a series of short pumping tests were run at increasing rates to reach approximate equilibrium. These are shown in the graph CD of Figure 3. These rates are higher than steady rates would be, owing to gains from rock storage, the reverse of the condition in graph AB. The middle graph is an adjustment to reconcile the storage effects, plus and minus, by taking account of time and of water quantities, and gives the best available estimate of steady rates at various elevations. The practically straight parts of the two upper graphs indicate N equal practically to unity. Below the 12-foot elevation the loss of inflow area as the water falls below the roof of the tunnel is shown in the increasing slope of these graphs. The closed curve, ABCD, of Figure 3, is essentially a hydraulic analog of the hysteresis loop of magnetism. The general findings of this test have been verified by several earlier tests, as well as by the drawdown-discharge relationship for a limited set of conditions permitted by operating requirements.

Summary and conclusion--Both by consideration of all the hydraulic conditions and dimensions, and by actual large-scale pumping tests, it has been shown that laminar flow must prevail throughout the Honolulu aquifer as a whole. This condition is shown to exist at multiple artesian-well stations, at single artesian wells, and at tunnel or shaft stations on a free water table where due account can be taken of changes of yield area.

Tests of the larger artesian-well stations show that turbulent flow does exist, as would be expected, in well casings, and also that some turbulent flow is found in the aquifer rock in the portion closest to the periphery of the well. Thus, individually determined values of N, differing from unity, and falling in the range from one to two, are found for such stations and are of great utility in calculating expected discharges under various changing conditions. They should be used, of course, only within the range of REYNOLDS numbers for which they were found.

On the other hand, by the same tests, it is just as conclusively shown that turbulent flow does not take place at distances of more than a few feet away from operating wells and no basis was found for supposing that turbulent flow, or values of N differing from unity, can obtain under any natural conditions remote from wells in the basal water body of the Honolulu aquifer. Consequently, for all calculations based on differences of head in the water table of one area, or from one area to another, we are fully justified in postulating laminar flow and using the value N = 1. This procedure, with proper regard for constant or changing cross-sectional areas, applies to all problems of ocean leakage, inter-zone leakage, and of the still little understood storage changes in the Ghyben-Herzberg lens.

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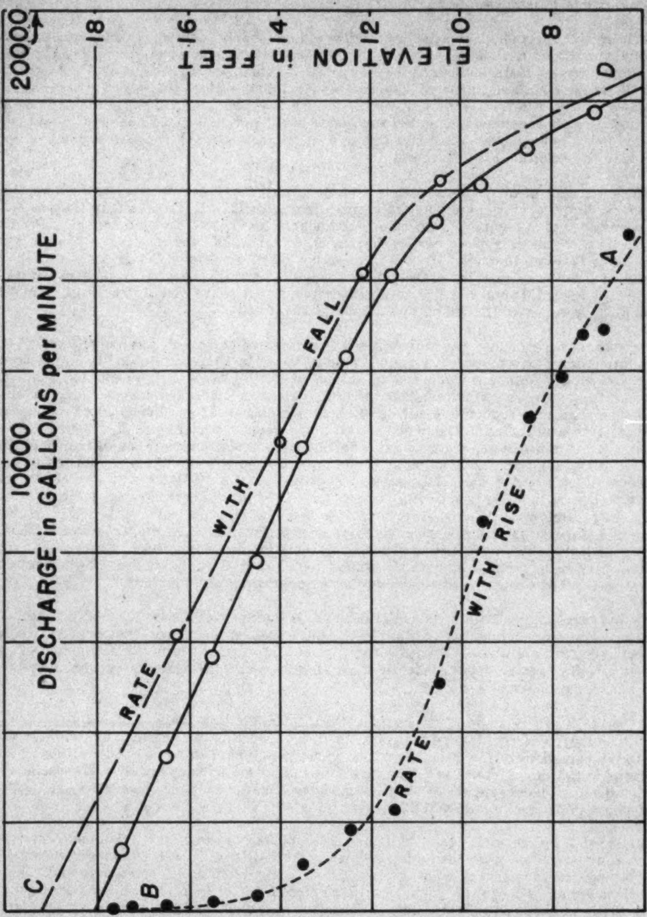

Fig. 3--Water levels and discharge rates for Halawa basal station [Data are from test made by shutting off pumps and allowing sump and tunnel to fill, after heavy pumping, followed by tests at various rates as described in text.]

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NOTE ON THE FREQUENCY DISTRIBUTION OF GEOTHERMAL GRADIENTS

H. Landsberg

Tables of temperature gradients observed in the Earth's crust have been compiled by H. C. SPICER [see "References" at end of paper, SPICER, 1942]. These data cover several pages, and it was considered convenient to summarize them for teaching purposes.

This was done by obtaining the frequency of various geothermal gradients for intervals of 2°C/km for the three intervals of depths given in the original tables, that is, 30.5 to 305 m, 305 to 610 m, and more than 610 m. Three frequency polygons were obtained, shown in Figure 1. Eight odd values over 62°C/km were omitted. The histograms for the two upper levels show distinctly

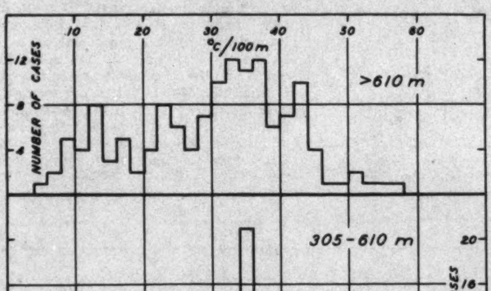

Fig. 1--Frequency distributions of geothermal gradients for three intervals of depths

bimodal distributions. In the 30.5-305-m group (198 observations) the maximal frequencies are the steps 18 to 20°C/km and 34 to 36°C/km. In the 305-610 m group (175 observations) the second mode is in the same interval as in the first group, but the first maximum lies in the somewhat lower interval of 14 to 16°C/km. The third group of data (138 observations), taken at depths of more than 610 m shows a main mode in approximately the same range as the other two groups with several minor modes. The irregularities in this last histogram might be attributed, in part, to the smaller number of observations in the third group.

In Figure 2 all the 511 observations are shown as a frequency distribution. This summation again emphasizes the bimodal distribution of the observations with a broad maximum for gradients around 12 to 18°C/km and a rather sharp main maximum for 34-36°C/km. This histogram is rather regular in appearance.

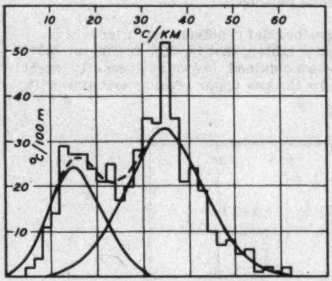

Fig. 2--Frequency distribution of 511 observations, showing bimodal distribution

As part of a statistical analysis of the data a plot of the cumulative percentage frequencies was made on arithmetic probability paper. This is shown as curve A in Figure 3. The points on this curve can be approximated by two straight lines. This, as well as the histogram of Figure 2, suggested that the distribution could be approximated by two normal frequency distributions. As a first trial to obtain these distributions, it was assumed that the values for one of these distributions are symmetrical around the 34 to 36°C/km class. In other words, the same value was assigned to each class interval to the left of the modal class as was observed to the right of this class. The remainder of the observed number of cases was attributed to the second distribution. If cumulative percentage frequencies are again plotted for each of the two distributions on the arithmetic probability paper, the points marked by circles for the first and crosses for the second distribution were obtained. Both sets of points fall close to straight lines (B and C in Figure 3). This confirms that two normal distributions are quite representative of the original data.

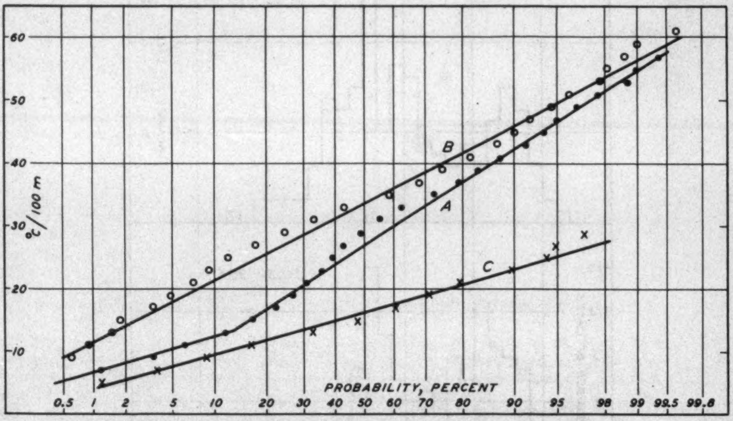

Fig. 3--Cumulative percentage frequencies (A) for all observations, and (B and C) for observations segregated by bimodal distribution

As a next step two normal curves were then fitted to the distribution. These are shown in Figure 2, where a summation of these two curves is also drawn. The summation curve fits the original data quite well with the exception of the interval 34 to 36°C/km, which shows a considerable inflation in the number of observations.

The existence of two such frequency distributions among the observed geothermal gradients suggests a natural cause. The most apparent explanation is that there exist two prominent heat conductivity values in the Earth's crust. If the geothermal gradient is produced by an essentially constant source of heat and a state of equilibrium has been reached, the gradient is determined by the conductivity according to the relation $dQ = -\kappa\Gamma$ where dQ is the heat flow, κ the thermal conductivity, and Γ the geothermal gradient.

Assuming that the heat flow through two different types of rock material is equal, the relation between the two heat conductivities and geothermal gradients is obtained:

$$\kappa_1/\kappa_2 = \Gamma_2/\Gamma_1 \qquad (1)$$

Using the modal values for Γ obtained from the two frequency distributions, this ratio is 35/15 or about 2.3. The thermal conductivity κ in cal per sec per cm per degree for igneous rocks is about 7×10^{-3}, for sedimentary rocks about 4×10^{-3}. This varies quite widely with pressure, rock type, bedding direction, etc. according to the available measurements. The ratio between these two values is 1.8. This quantity is not too different from the ratio of the geothermal gradients.

Therefore the hypothesis may be advanced that the observed geothermal gradients are caused by these two basic heat conductivities with random variations around them according to pressure, density of the rocks, and share of each basic type in the strata through which the measurements have been made.

With geothermal measurements from some regions rather preponderant over others even the inflation of certain steps in the frequency distribution can be explained.

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A PORTION OF THE SAN ANDREAS RIFT IN SOUTHERN CALIFORNIA

Robert E. Wallace

Abstract

An area approximately 20 miles long and five miles wide along the San Andreas Rift in Southern California between Palmdale and Elizabeth Lake was mapped and studied. The area includes a portion of the Mohave Desert and two ridge zones which are separated by the trough that follows the Rift.

The ridge zones are principally old crystalline rocks, whereas the trough is underlain by a long, narrow strip of sediments. These sediments outcrop in a low "center-trough" ridge, and most of them are part of the Anaverde formation, which, on the basis of paleobotanical evidence, is believed to be transitional between lower and middle Pliocene in age. Evidence indicating how this long strip of sediments came to be in the present relationship to the crystalline rocks on either side is of a conflicting nature. The older rocks of the ridge zones are in irregular bands striking east or slightly north of east. This trend is cut by the Rift, which in this area has a strike of approximately N 65°W.

Offset of terrace deposits suggests a horizontal displacement along the Rift of the order of five to six miles since the Pleistocene. Streams are offset as much as 1-1/2 mi. The north side of the Rift has moved southeastward with respect to the south side. Blocks of Pelona schist on opposite sides of the Rift are so situated as to suggest displacement of nine miles in the opposite direction to that indicated by recent faulting. This displacement is believed to be only apparent and possibly the result of vertical uplifting of two separate Pelona schist blocks. Many and frequent vertical displacements of various blocks are indicated by elevated terrace deposits and old erosion surfaces.

There is no definite evidence to demonstrate that strike-slip displacement originated earlier than the Pleistocene period, although suggestions of greater age of the Rift are found.

Strike-slip displacements similar to the San Andreas Rift are apparently widespread in Southern California, suggesting that stresses have been applied sub-equally throughout a large area, possibly by drag from sub-crustal currents.

U. S. Geological Survey,
Washington, D. C.

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GEOPHYSICAL AND GEOLOGICAL EDUCATION

Foreword--The following three papers are the formal papers presented at the Session on Geophysical and Geological Education, of the Section of Tectonophysics at the Twenty-Seventh Annual Meeting of the American Geophysical Union, Washington, D. C., on May 28, 1946, under the chairmanship of CHESTER R. LONGWELL. This is the third such session; the first two were held by the Geological Society of America in Pittsburgh, Pennsylvania on December 27 and 28, 1945; and by the American Association of Petroleum Geologists in Chicago, Illinois, April 3, 1946.

The discussions presented at these two sessions have been published by the Geological Society of America as Interim Proceedings for 1946, parts 2 and 4, and it is anticipated that the complete discussion of the session of which the following papers are a part will be published as Part 5 of those Proceedings--Ed.

TRAINING FOR RESEARCH IN GEOPHYSICAL BORDERLANDS OF GEOLOGY

Maurice Ewing

To prepare myself for this discussion, I read through a good many papers on various aspects of the academic training of geologists. The problem of improving this training has been the subject of many symposia and individual papers, and almost every tenable point of view has already been set forth in a more able form than I could hope to match. In brief, everyone agrees that we need students who know a lot more about everything. Especial mention is made of the basic sciences--mathematics, physics, chemistry, and biology--although many writers feel that literature, history, languages, etc. are neglected. My decision was to treat the subject from a personal point of view; to describe how I have tried to meet this problem in the past and how I propose to meet it in the future.

In evaluating the merits of the type of training given in the past to those now engaged in geophysical research, it must be kept in mind that the scientists of the United States have undoubtedly led the World in the relatively new field of geological prospecting; and that very few of them have had any formal instruction in geophysics or in any combination of sciences which we might consider ideal preparation for this work. They might have done a better job, it is true, with better preparation, but they did well enough as it was to achieve worldwide superiority in their field. If you examined the work habits and training of any one of these men to decide what was responsible for his success, I believe you would find that he had thoroughly mastered some one discipline, and, with this as a background, was able to extend his efforts to the new field. He had formed the habit of mastering that part of any problem with which he personally dealt, and of knowing when he could speak with authority and when to seek the advice of someone better informed than himself. Such training and habits of work are, of course, of fundamental importance for success in any field.

However, I heartily agree that we need a better type of graduate student in geology and geophysics--a better-trained student entering the graduate schools. I have only recently begun a critical inspection of the qualifications of this class of student, but I believe that the group I have been observing is typical. It was a great shock to discover that the level of training in the basic sciences in the lower half of this group of students approximated what I was taught as an undergraduate to expect of every person holding a bachelor's degree. For example, many people think that the study of mathematics through the simple parts of differential and integral calculus should be required for a bachelor's degree in any subject, and the lower half of the students applying for graduate training in geology just barely measured up to that standard. It is an alarming situation if students who have devoted their undergraduate years to preparation for any field of science, end with barely the general scientific training expected of those majoring in English literature, history, etc.

I have a proposal to remedy this situation, which I tried out in a small way before the War while teaching at Lehigh University. There I gave an undergraduate course in geophysics which was relatively unimportant as a course, but which in a few years' time produced a number of students who did exceptionally well when they entered commercial work. I have been proud of the individual students and proud of their number. The function of this course was simply to make the students state their interest in geophysics formally to themselves and agree to plan their curricula accordingly. Its chief benefit was not the material it offered, but the opportunity it gave to find the students two or three years before graduation and to advise them how to round out their scientific training. I had physics majors, geology majors, electrical engineering majors, and in every case it was possible to give them a more thorough training and to make them more valuable for work in geophysical prospecting by advising them to pick their electives in a manner they would not otherwise have chosen. Physics students, for example, were urged to take some geology. We advised each student to look at the rest of the curriculum with a definite view to plugging the more obvious holes in his training. From an examination of the catalogues of other universities, it appears also possible to greatly improve a man's preparation, while remaining within the limits set by their rules and regulations, by advising him to take at least a sample of other parts of the curriculum. For it is as important for the geologist or geophysicist, as for the premedical student, to decide on the goal of his undergraduate work early in his career.

In the larger eastern universities there appears to be little or no contact between undergraduates majoring in geology and professors of geology in the graduate schools. In many universities I gather that only a small or negligible per cent of the graduate students are drawn from the corresponding undergraduate schools. Some of the earlier reports of this committee point out that this is an astonishing and incredible situation.

Now my proposal amounts to a recommendation of considerable personal acquaintance between professors in the graduate schools and the undergraduates who are their potential graduate students. This can sometimes be carrier further. Professor THOM, for example, has sometimes worked with high-school students in his summer camp at Red Lodge. I do not know what sort of revolution would be required to organize the teaching programs of the universities so that students in elementary geology courses would have the opportunity to meet the men who could inspire them to make an early selection of a particular field of geology. But these are the men under whom they will be working a few years later and who could best advise them how to plan their curricula; and I firmly believe that the professor who devotes some of time and effort to the recruiting of students in their early undergraduate years will be amply repaid by the quality of the students thus produced. This method may be difficult to put into effect, but it is the only specific, practical step which I can recommend as a remedy for the present situation, and it is one which I have found in practice to give results. I am convinced that it will help me, and any individual teacher who uses it, in the search for good graduate students; and that if we all use it, it will effect a great improvement in the general type of student entering graduate school four or five years from now.

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TRAINING GEOLOGISTS FOR SERVICE IN THE CIVIL ENGINEERING ORGANIZATION

Edward B. Burwell, Jr.

The subject of training geologists for the field of civil engineering is one of great interest to me, because my entire professional efforts for the past 16 years have been given to providing geologic information for the use of engineers. This field of applied geology is coming to the foreground, not so much because of the activities and publicity it has received from the geological profession, but because of the large and growing demand by the engineering profession for a better understanding of the geologic factors involved in heavy construction engineering. During the past 15 years, the demand for professional geologic services has grown from an occasional call for advice from the consultant to the full-time utilization of large geologic groups composed of personnel trained and equipped for service in the civil engineering organization. The outstanding demand has come from the agencies of the Federal Government entrusted with the control and development of the Nation's rivers. The current and projected plans of these agencies for flood control, navigation, irrigation, and hydroelectric power developments are widespread in scope, extending into every major river basin of the country. The geologist is to play an important part in the development and consummation of these plans. Therefore, it is a responsibility of our institutions of learning to provide the requisite background of atmosphere and training for the students of geology who are to enter this important field.

The geological profession, in general, has been slow in taking advantage of the great opportunities offered it in the field of civil engineering. Our universities and geological societies and agencies have been slow in creating an atmosphere conducive to rapid growth and development of the engineering applications of geology. Perhaps our major handicap has been our intense interest in things purely geological and our unwillingness to work in or for the advancement of a specialized field which offers so little opportunity for scientific research. But now the demand for professional geological services in civil engineering is too large for us to delay longer in giving this field of application of the science a prominent place in the activities of our universities and societies.

Naturally, my approach to the subject of training of geologists for the field of civil engineering is influenced by the concepts that I hold concerning the question: What are the proper functions and responsibilities of the geologist in the engineering organization? This is a somewhat controversial question, because there are those who believe that the functions and responsibilities of the geologist end when he has made the necessary geologic discoveries and deductions and advised the engineer of them. I may say at once that I do not hold to this concept. On the contrary, it is my belief that the geologist in responsible charge should have sufficient knowledge of design and construction problems and of stability requirements to give advice on these matters, and should be able to be of material assistance in the solution of these problems.

Such matters as foundation treatment, excavation methods, stability of slopes, uplift assumptions, sliding and shear coefficients, cut-off and grouting treatment, foundation settlement, and foundation rebound are engineering problems. But who is in a better position to appraise them than the geologist, if he has had the proper training and experience? I hold that the geologist, however competent he may be in the field of geology, is not fully equipped to be in responsible charge of geology on a large civil engineering undertaking unless he is competent to give sound advice and even make decisions on these and many other similar engineering matters. It seems to me that failure of the engineering profession to give greater recognition to the geologist sooner was more largely a result of the geologists' academic approach to practical problems than of a lack of appreciation of geologic factors on the part of the engineer.

With these introductory remarks we come to the topic of our discussion: What courses of training should be provided for geological students who contemplate entry into the field of civil engineering? It is certain that they will need the same background of geologic knowledge as the students who are to work for a geological agency or a mining corporation, or are to become teachers of geology, for almost the entire field of the science must be brought to bear in providing the engineer with all the geologic information he should have. Physiography, historical geology, stratigraphy, structural geology, petrology, economic geology, ground-water hydrology; all of these subjects have important applications in construction engineering. Therefore, the basic difference in requirements is one of knowing more about the fundamentals of engineering and of being temperamentally equipped to deal with the practical problems of engineering than of knowing more about certain branches of the science of geology. By this I do not mean to infer that certain branches of geology should not be stressed. Special emphasis should be placed on structural geology, stratigraphy, and petrology, because the geologist's ability to discover and appraise the geologic details which bear so forcibly on design and construction problems will depend largely upon his competency in these branches of geology. Proper training in these subjects, of course, involves a generous amount of field geology.

The engineering geologist should be thoroughly trained in ground-water principles and ground-water hydrology. Reliable appraisals of dam and reservoir sites frequently depend more upon adequate knowledge of ground-water conditions than upon any other phase of geologic knowledge, and sometimes the entire feasibility of a project depends upon this knowledge. I am under the impression that the courses of training in this highly important subject are much too limited to equip the student adequately for work on important construction projects.

The student preparing for geological work in engineering should be well grounded in the theory and practical application of soils mechanics. This newest branch of applied geology has, unfortunately, become the adopted child of engineering. And this adoption has come about through the failure or inability of the geological profession to recognize its offspring and nurture its growth and development. Perhaps inability is the more judicious word, because I do not believe that geologists in general have been adequately trained in physics, mathematics, and mechanics to undertake work in the field of soils mechanics.

Geophysics also has a useful application in civil engineering, though, in general, its scope and the magnitude of its problems in engineering are not such as to require the employment of a highly-trained and experienced geophysicist. We have found that alert-minded geologists and engineers can, within a reasonable period of training, become efficient operators of geophysical

instruments of the type used in foundation explorations. The geologist, if he has sufficient training in physics, mathematics, and the fundamentals of electricity, should be better equipped for this work than the engineer, because of his knowledge of geology. A course of training in the theory and application of geophysical methods should, I believe, be included in the curriculum for the students of engineering geology.

Geology, if it is to meet the needs of engineering, must go much farther into the quantitative phase. This, of course, necessitates a great deal more emphasis on the basic sciences on which both geology and engineering depend, namely, mathematics, physics, and chemistry. It seems to me that the geological student training for work in the civil engineering field should have the same basic undergraduate courses in physics, mathematics, hydraulics, statics, dynamics, and strength of materials as the student training for the profession of civil engineering. How to accomplish this in four years and supply the fundamental requirements in chemistry, general geology, mineralogy, crystallography, petrology, paleontology, stratigraphy, structural geology, field geology, and surveying, in addition to the required time for a foreign language and the social sciences, is admittedly a difficult problem. Perhaps the closest approach to the desired requirements would be an undergraduate course patterned after that of the student of mining engineering, with an added dosage of geology being substituted for the purely mining subjects. In any event, the fundamentals of engineering should not be neglected in order to give the student more geology during his undergraduate years.

Assuming that the student has had at least two summers of field work, the essential graduate work can probably be accomplished in one year. The graduate courses should include structural geology, stratigraphy, petrography, economic geology, soils mechanics, geophysics, ground-water hydrology, and a generous course in the application of geology in engineering. Excellent subject material for the last can be found in LEGGETT'S Geology and engineering and in various publications and reports on many of the major civil engineering projects. It should be taught, if possible, by experienced engineering geologists.

The course of training in applied geology should include such subjects as methods and techniques of foundation explorations, methods and techniques of testing foundation materials, methods of presenting information for the use of engineers, methods and techniques of foundation treatment, construction materials and their requirements, and the geologic problems of dams, reservoirs, artificial waterways, tunnels, and bridges, and the problems of landslides, earth movements, and earthquakes.

Obviously the adequacy of the training which has been outlined in producing successful engineering geologists will depend largely upon the mental fiber and temperamental make-up of the raw material. It has been said that the student of only average intelligence should seek some other vocation than geology. I would add that the student deficient in the common garden variety of horse-sense should, if he must be a geologist, pursue some other branch of the science than engineering geology.

[Note: The above paper, the one preceding, and the one following are the formal papers presented in the panel discussion on Geophysical and Geological education held by the Section of Tectonophysics at the time of the Annual Meeting in May 1946. The full proceedings are to be published soon as Part 4, Interim Proceedings of the Geological Society of America, 1946. Copies may be secured from the Geological Society of America or the American Geophysical Union.]

War Department,
Washington, D. C.

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ACCREDITING AS A MEANS OF IMPROVING UNDERGRADUATE TRAINING IN SCIENCE

M. H. Trytten

In recent weeks I have been in consultation at the Capitol to talk about the future of the Selective Service Act. I was particularly struck by the sentiment even now among senators against any differentiation in treatment for highly-trained scientific personnel. I have been afraid that this basic issue would be avoided by successive temporizations as the Selective Service Act was extended a little at a time. I still think that that is what will happen. In the kind of civilization in

which we live I know you agree with me we need to be very careful to provide for a supply of specialists. That realization, I am afraid, is not going to occur in the minds of Congress. But that is a digression.

I do not present this paper as an advocate of accreditation. I do, however, want to tell you some of the things that I believe are indicative of a trend in that direction. Recently I have attended a number of meetings at which this matter was under discussion.

The American Council on Education, at its recent meeting in Chicago, devoted an evening meeting to problems of accreditation. The interest of that particular group was in the problem that faced the universities and colleges in furnishing information on which accreditation rests; accreditation of colleges is now done by a number of regional agencies which overlap and by agencies such as the Association of American Universities, and so on. Furnishing the necessary information does provide quite a bit of work for the individual college. Similarly, I attended a meeting at Atlantic City of the American Chemical Society recently where much attention was given to the subject. The difference of opinion with regard to the need for accreditation was striking. Even in our own field of physics there is some preoccupation with the problem at the present time. The Executive Committee of the American Association of Physics Teachers has considered the problem from the standpoint of the physics teachers. The membership of this Committee came to the conclusion that they could not ignore the problem much longer. Accreditation is fundamentally against our national habits of thought. We all have the pioneering instinct strongly even yet. We like freedom and do not like regimentation. There is no question but that accreditation is a form of regimentation and may lead to undesirable academic rigidity. I do not think we can doubt that the danger is there. The question is why these groups feel the need of accreditation. It is obvious in case of those professions in which licensing is necessary. Accreditation, for example, is a well-recognized procedure for medical and dental schools. These professions are very highly organized and have had long experience with licensure. It is the same in the case of the engineers--they are very highly organized and have an advanced program of accreditation. Licensure for engineering is also required in most states if not all of them. The chemists are face to face with the problem now because a certain number of states actually have laws in preparation calling for the licensing of chemists. Ohio and Illinois are examples. I do not know that any state has actually passed such a law. It is worth noting in passing that if licensure is required by law in any field, it raises interesting questions in neighboring fields. For example, I can well imagine that a geologist doing essentially geological engineering and who prefers to be unlicensed might find himself in difficulty in certain states requiring the licensing of engineers. There are certain things that chemists can do and certain things they cannot do, I understand, in view of the licensing of neighboring health fields. This much, at least, raises the question of whether any field can remain wholly aloof from the problem. Those problems of licensure are, I hope, far away from the physicists, and the geologists, but it is not unlikely that they may someday emerge as major issues.

In regard to the need for accreditation, it seems to me that some of the experiences of the past War have indicated that accreditation may be very useful, if not necessary, in the future in some of the fields in which it has not been thought of before. I have been very close to the problem during the wartime period. In the early days of the War there existed a Federal Loan Fund operated by the United States Office of Education. In the administration of that Loan Fund the United States Office of Education found it necessary to set up rules and regulations to determine eligibility for the loans. This was done only with a great deal of difficulty in the field of physics, with which I am most familiar, and I am sure in other fields there were similar experiences. The problem was difficult because of the lack of a legally determinable criterion for selecting approved institutions or approved curricula. An arbitrary rule was of necessity adopted and proved to be unsatisfactory. Any future similar program will encounter the same obstacle to its administration.

The Selective Service Act furnished another example. Early in the War some attempt was made to defer persons in training in the colleges and universities in especially critical fields, and to defer highly-trained personnel. One serious obstacle leading to the breakdown of such a principle was the lack of a clear-cut differentiation between professionally-trained scientists and the graduate partially trained in science. As a result, procedures depending in part on qualifications were abandoned, and any attempt thereafter to speak in terms of a supply of scientists failed.

The United States Civil Service presents a similar problem. Up to about 1944, the Civil Service Commission was in the habit of requiring a Bachelor of Science degree or Bachelor of Arts degree for entrance to Civil Service examinations to establish eligibility registers for use in geology and other scientific fields. Then Congress passed the so-called Veterans' Preference Act, which contains a clause stating that no general minimum educational requirements shall be stated for Civil Service examinations except in those cases in which the required competence cannot be achieved in any other way. This law was interpreted strictly. Only in the case of the professions where state licensure was required would they publish any minimum educational requirement at all. Recently it has been possible to get the Civil Service Commission to modify that interpretation considerably, and the present ruling is generally satisfactory. For research positions it required that the individual applicant complete a standard four-year college course. In this whole discussion about the bill, the one recurring point that was raised was this one: That to require a degree from an American college as a prerequisite to examination is not appropriate because it is not usually a recognized measure of competence or accomplishment, since curricula vary so much in content, in degree of saturation with the core subjects, and in quality. Until there is more uniformity of practise there is no point to using the degree as a uniform requirement.

There are a couple of other instances to which attention may be called, looking to the future. There is a good deal of thinking now in the War and Navy Departments about the status of scientists in any future national difficulty. I do not know that any of this thinking has gotten to the point at which it exists in any published or written document. I suspect when a final proposal comes out, let us say, from the War Department or the Navy Department, calling for setting up something in the nature of a scientific corps, then the problem of minimum standard requirements for such a corps will immediately confront the scientists. Again another future possibility is worth notice. If the Science Foundation Bill passes, it will incorporate provisions for scholarships and fellowships in the sciences. Since this will be a government operation under law, uniformity in procedures and administration will be necessary. Political pressures will force such uniformity to avoid political trouble. Such uniformity will need to depend on written criteria. Scientists would be in a better position if they could set up uniform criteria rather than have it done by necessitous Federal administration. Written rules, of course, cannot guarantee quality. I saw recently records of examinations in 22 engineering schools given by the graduate record examiners. Ninety-eight per cent of the students of one school ranked ahead of all of the students from another school.

The problem of accreditation is not a problem of guarantee of scholarships. It is rather a matter of establishing certain minima, and yet the protection of standards of quality may be important as one looks into the future. I have been very much struck by the reports that have come out on veteran enrollment during the past month. There are two reports, as you know, one of them published by the United States Veterans Administration, the other, the Snyder report, a more pretentious document by the Office of War Demobilization and Reconversion. Both of them attempt to give a measuring look at the tidal wave coming to the universities this fall. The Veterans Administration reports that there will be an enrollment of about 1,500,000 in the fall with reported space for 1,600,000. This apparently leaves unused space for 100,000 in the colleges in the fall. I think anyone will know that that picture is not a likely one. This result reflects the questions asked by the Veterans Administration. Actually what they did was to ask the colleges, "How many do you plan to take and how much space to you have?" Obviously, those institutions that intended to take as many students as they had space for reported that fact. Those institutions that expected an enrollment smaller than they had space for so indicated on the questionnaire. The report, therefore, does not reflect the greater demand. The Snyder report reflects three surveys in which Army and Navy personnel were asked if they intended to go back to school. The first was made quite a long time before most of the veterans, soldiers at that time, knew what the provisions of the so-called GI Bill of Rights were. The second survey reveals the attitude of the soldier after he has been informed of his privileges under that Bill. The third is a check. The probable enrollment is 2,080,000. Somewhere in the neighborhood of 300,000 to 400,000 persons probably will not be able to go to college, accepting the figure on facilities provided by the Veterans Administration report. This report assumes that every person who wants to go to college should go to college. Now, of course, as you know, most institutions do not figure that way. Many admit the upper 40 to 60 per cent from the high schools. This report advocates that every veteran who wants to, has the right to go to college under the GI Bill of Rights, and we are morally bound to try to see to it that he gets a place in an institution of higher learning somewhere. I think it has a great deal of pertinence to this discussion because it seems to me that it would be very difficult, indeed, to keep up standards in American colleges if this philosophy prevails. It will have the effect which it has had in high schools in the past years. There is a leveling effect by the admission of these persons to the high schools, and it must happen in the colleges also. What is the antidote? I can not see it anywhere else except that the professional and scientific societies themselves make some effort toward the protection of standards.

National Research Council,
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EARTHQUAKE STUDY IN SOUTHERN CALIFORNIA, 1945

B. Gutenberg and C. F. Richter

(Contribution No. 385, Balch Graduate School of the Geological Sciences)

This continues the previous report of GUTENBERG and RICHTER [see "References" at end of report, 1945 a]. Three papers reported as in press in 1945 have since appeared [GUTENBERG, 1945 a and b; GUTENBERG and RICHTER, 1945 b]. WOOD'S paper [pending] on local epicenters and fault structure in Southern California has been submitted to the Seismological Society of America.

As the first paper of GUTENBERG and RICHTER [1941] on seismicity of the Earth is now out of print, a revision has been undertaken, incorporating the results of the supplementary paper [GUTENBERG and RICHTER, 1945 b] and much new material. No epicenter has been accepted from the International Summary or any other source without careful revision. A large file of individual station bulletins has been accumulated through correspondence, as exchange or on loan. This has facilitated assigning magnitudes, and has much improved the statistics of large shocks. Magnitudes have been assigned to all shocks, shallow and deep, of magnitude 6 or larger, used in the study. For further statistical investigation the data have been entered on punch cards, which now number about 2500 for shallow earthquakes, and over 1000 for deep shocks. It is hoped that it will be possible to publish the full list of epicenters.

The largest shocks (1904 to 1945 inclusive) are shown in Table 1.

Table 1--Largest earthquake shocks, 1904 to 1945

Shallow shocks magnitudes near 8-1/2		Intermediate shocks magnitudes near 8			Deep shocks magnitudes 7-3/4 to 8		
Date	Location	Date	Location	Depth	Date	Location	Depth
				km			km
Jan. 31, 1906	Colombia	June 16, 1910	Loyalty Is.	100	Jan. 21, 1906	Japan	340
Aug. 17, 1906	Chile	June 15, 1911	Ryukyu	160	May 26, 1932	Tonga	600
Jan. 3, 1911	Tien Shan	Nov. 24, 1914	Marianas	110	Apr. 16, 1937	Tonga	400
Dec. 16, 1920	Kansu	June 26, 1926	Rhodes	100			
Mar. 2, 1933	Japan	Dec. 21, 1939	Celebes	150			

These shocks account for most of the release of energy in each group. The average annual energy release in units of 10^{26} ergs is about 10 for shallow shocks, 1.3 for intermediate shocks, and 0.3 for deep shocks. Although these figures may be in error by a factor 10, they are nevertheless comparable with the corresponding figures for energy transfer in secular internal cooling of the Earth, which is about one-tenth that for energy released in radioactive processes in the Earth's crust. Fluctuation is large; individual years range from 25 to 0.5 of the same units, with the exceptional year 1906 at 65. For shallow shocks the mean activity is roughly constant from 1904 through 1943. For deep shocks there is a decrease from about 0.5 to about 0.2 units in the same period. There are long intervals of relatively low activity in the intermediate depth range. For example, between October 19, 1929, and May 23, 1938, there was no intermediate shock with magnitude over 7.3.

The number of large shocks falls off rapidly with increasing depth to about 300 km; between 300 and 700 km the distribution in depth is fairly even, and then falls to zero abruptly.

For an increase by one unit of the magnitude, the frequency of occurrence decreases to about 1/8 for shallow shocks and about 1/13 for intermediate and deep shocks. For the largest shocks--above magnitudes of 8-1/4 in shallow shocks and above 7-3/4 in intermediate and deep shocks--the numbers decrease faster. On the average there are about 14 shocks annually of magnitude 7

or more, about 100 of magnitude 6 to 7 and (estimated) half a million of magnitude over 2. There are about four intermediate shocks and one deep shock annually of magnitude 7 or over.

For correlation with seismic data, JOHN M. NORDQUIST has compiled a list of active volcanoes from numerous sources. This is being verified and extended by correspondence.

The typical features and phenomena associated with active arcs of Pacific type [GUTENBERG and RICHTER, 1945 b, pp. 654-661] have been rediscussed. Further data are now available on the analogous but less active arcs of the trans-Asiatic Alpide belt, particularly in the Mediterranean area. Intermediate shocks occur in the belt principally under sharp flexures in the surface structures, and are frequently associated with active volcanoes and gravity anomalies.

B. GUTENBERG was placed under contract by the Navy Department as technical adviser and consultant for its project on the use of microseisms in hurricane detection [ORVILLE and GUTENBERG, 1946]. Among his unpublished findings is the result that microseisms are propagated only to relatively short distances in the Caribbean area, with rapid loss of energy in crossing the major structural discontinuities.

Study of seismograms for the New Mexico atomic bomb test of July 16, 1945, shows that Pn was recorded at Tucson, Palomar, and Riverside, with a velocity of 8.0 km/sec. Air waves of various velocities were recorded by seismographs at no less than ten stations.

A study of the larger California shocks for which instrumental records are available is being prepared by C. F. RICHTER and J. M. NORDQUIST.

A portable seismometer was dispatched into the area of the large shock of March 15, 1946. The records of aftershocks were valuable in locating the source of the main earthquake, which is tentatively placed at 35°44′ N, 118°02′.5 W, with 0 = 13:49:36 U. T. (05:49:36 PST), and magnitude about 6.4.

Routine bulletins for teleseisms have been prepared through 1945; those for local shocks are in course of completion.

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RECENT DEVELOPMENTS IN OCEANOGRAPHY AT THE UNITED STATES NAVY HYDROGRAPHIC OFFICE

R. O. Glover

Introduction

For the past two or three years in his reports published in the Transactions of the American Geophysical Union, my predecessor, Admiral BRYAN, has hinted at the work carried on at the Hydrographic Office to meet the oceanographic needs of the services during the War and has emphasized the need for a permanent organization to continue this work. When you hear a little more of our accomplishments during the War and of our plans for the future, I think that you will agree that we have been through a period of revolution and are now starting on a new era in the study of the sea.

It gives me great pleasure to inform you that BRYAN'S fondest hope was realized just prior to his retirement; a Division of Oceanography has now been established to provide for the additional responsibilities assigned to the Hydrographic Office by the Secretary of the Navy.

Oceanography during the War

The development of modern global warfare made it necessary to obtain types of information not previously of much concern to either the Army or Navy. Oceanography was one of the fields of great interest. A knowledge of the oceans proved essential in submarine warfare, in air-sea rescue, in amphibious operations, and in the development of underwater ordnance.

To provide the necessary information for the Armed Forces, an extensive oceanographic research program was initiated by the Hydrographic Office and the Bureau of Ships. With the assistance of the National Defense Research Committee and through contracts administered by the Bureau of Ships, the Woods Hole Oceanographic Institution and the University of California were able to provide facilities and additional personnel for the expanded program. This made it possible to carry on the basic research and analysis of data under the direction of the best oceanographers and through them to obtain the assistance of numerous scientists formerly working in allied fields.

The Oceanographic Unit, mentioned last year by BRYAN, was set up in the Hydrographic Office to coordinate this program. This Unit was chiefly concerned with editing and with expediting the publishing and distribution of oceanographic charts and manuals for the fleet and the amphibious forces, as well as with preparing the oceanographic chapter for the Joint Army and Navy Intelligence Studies, numerous short reports for the Joint Chiefs of Staff, and tactical reports for various activities in the fields.

In carrying out its wartime program, the Hydrographic Office has been concerned with the following phases of oceanography: (1) Studies of sea, swell, and surf, which have had numerous applications and involved theoretical and experimental investigations as well as field measurements; (2) re-examination of permanent currents for many parts of the ocean and investigation of the character of tidal and wind-driven currents; (3) study of the distribution of temperature and salinity and their variation with depth, season, and time of day; (4) determination of topography and character of the bottom in shallow water; (5) investigation of the character of beaches and their changes during storms; (6) studies on the distribution and behavior of fouling and sound-producing organisms in the sea; and (7) study of the interaction between the sea and the atmosphere.

Examples of the products of these studies are now available, and I hope that those interested research activities can be provided with copies during the coming months. It is the policy of the Hydrographic Office that all material not concerned with specific military applications will be declassified and hence made public. This applies to much of the material produced during the war years and to future work, which we hope to distribute both here and abroad.

It appears that in calling on her civilian oceanographers to cooperate in the practical applications of oceanography, the United States differed from the Axis nations, for neither the Germans nor the Japanese sufficiently trusted their civilian oceanographers to give them the opportunity to adapt their independent research to wartime needs. In Germany, while some of the oceanographers worked for the military, they apparently were not informed of the problems involved. In Japan, on the other hand, the civilian oceanographers continued their peacetime work as best they could, and the Navy independently maintained its own oceanographers. Despite the fact that 95 vessels were used to collect oceanographic data, very little practical use was actually made of these observations by the Japanese.

The Division of Oceanography

The value of the contributions made during the War, the magnitude of the problems involved, and the numerous agencies interested in oceanographic problems indicated the need for a central agency to coordinate the program, to provide the information needed by the Navy Department, and to serve as a repository and clearing house for basic information. To meet this need the Secretary of the Navy directed that the Division of Oceanography be established as a permanent part of the Hydrographic Office.

It is the purpose of the Division to serve not only the military requirements of the Navy, but of other governmental agencies as well, the merchant marine, civil aviation, and the scientific world. To coordinate work in both basic and applied oceanography among governmental activities, the Office of Research and Inventions of the Navy Department has established a Governmental Advisory Committee on Oceanography. In addition to a number of bureaus, offices, and laboratories of the Navy Department, the following non-naval activities are represented on this Committee: United States Army Intelligence, United States Army Engineers, United States Army Air Forces Weather Division, Beach Erosion Board, United States Coast Guard, United States Weather Bureau, United States Coast and Geodetic Survey, United States Geological Survey, Fish and Wildlife Service, and the Smithsonian Institution. This Committee will make recommendations concerning the program of the Division of Oceanography, and the individual members will act as liaison officers for problems of mutual interest.

The future work of the Division will be in five general categories, and in each of these will deal with the fields of investigations which I mentioned a few moments ago in connection with the wartime program. These fields represent a tremendous sphere of research that is interrelated with the work of many other activities, such as those concerned with military geology and meteorology, underwater sound, subsurface warfare, and so forth. The functions of the Division are as follows: (1) To establish and coordinate programs for the systematic collection and analysis of oceanographic data; (2) to serve as a central repository for all types of oceanographic data; (3) to carry out research both in the Hydrographic Office and under contract at private laboratories and institutions, and to publish various types of data and reports; (4) to provide assistance and equipment in special problems of applied oceanography of military interest; and (5) to prepare charts, manuals, and publications of direct interest to the Navy.

It is expected that publications issued will take the following forms, although the titles are still tentative: (1) Atlases and special charts showing the oceanographic conditions at different depths and seasons; (2) technical reports based upon work done in the Division of Oceanography and by contractors; (3) manuals and nontechnical discussions dealing with such oceanographic problems as methods of taking observations, prediction of sea and swell, and so forth; (4) records of oceanographic observations, which will include tabulations of data collected by private and governmental activities, as well as by the Hydrographic Office; (5) Bibliography in oceanography, which will be issued periodically (two or three times each year), and will contain references to foreign and domestic publications. Cumulative bibliographies dealing with special problems or areas will be issued as technical reports; (6) Oceanographic newsletter, a quarterly summary of the oceanographic work of the activities represented on the Governmental Advisory Committee on Oceanography, carried on at private research institutions, contractors of the Hydrographic Office and the Office of Research and Inventions, and in the Division of Oceanography; and (7) papers in scientific journals, both here and abroad, prepared by the staff of the Division of Oceanography.

Several publications mentioned last year by BRYAN have been published or are about to be published: The Ice Atlas of the Northern Hemisphere, H. O. Pub. 550, is now being printed; the Bibliography on ice of the Northern Hemisphere, H. O. Pub. 240, has been issued; Wind waves at sea, breakers and surf, H. O. Pub. 239, by H. B. BIGELOW and W. T. EDMONDSON, is now in press; References on the physical oceanography of the western Pacific Ocean is now being assembled for printing; a bibliography on surface wave motion is now being prepared; and Wind, sea, and swell: Theory of relations for forecasting, prepared by H. U. SVERDRUP and W. H. MUNK, has been received and will form the first of the technical publications in oceanography.

Among recent acquisitions of the Hydrographic Office of particular interest is the large amount of unpublished oceanographic data collected by the Japanese. These data cover many areas for which there existed no published material and therefore are of great value. A paper concerning these data is published elsewhere in this issue.

H. H. HESS has prepared a paper including three bathymetric charts of the western Pacific, prepared by the Division of Chart Construction, which will be published later. The great numbers of soundings accumulated at the Hydrographic Office during the War have made it possible to delineate the topography of the ocean basins in much greater detail than ever before. I am sure that you will be interested in the many new features shown on these charts.

The Division of Oceanography is now in a period of transition. Military personnel assigned to the Oceanographic Unit during the War are being demobilized, and civilian personnel are being recruited to fill the nine professional billets available for 1946-47. I am happy to report that RICHARD H. FLEMING has now assumed his new duties as Chief of the Division. Unfortunately, he will have little assistance in carrying on the work of the Division for the time being; at the present moment virtually every available oceanographer is involved in the Operation Crossroads, but by autumn we hope to have the authorized complement. In the coming years we will attempt to increase the staff in order to provide the facilities so urgently needed.

In order to foster basic research, a large fraction of the funds of the Division of Oceanography will be used to support contracts at universities and private laboratories. This will serve not only to insure that important research is conducted by those best qualified to supervise the programs, but also to stimulate and train graduate students to fill positions which will become available in the Division of Oceanography and elsewhere in the government service. It is believed that the Office of Research and Inventions will also have funds available and will support basic oceanographic work at private institutions when the problems are of interest to the Navy.

The plans for the coming year have not yet been formulated in detail, but it is expected that much of the effort will be devoted to completing compilation of data begun during the War, the analysis and systematic studies of current observations, of temperature and salinity, and of sea and swell, and the publication of various technical reports.

Plea for oceanographic publications

Before I conclude, there is one more point I wish to mention. In order to maintain a bibliographic service and to have available source material, it is necessary that the Hydrographic Office library be built up in oceanography and related fields. In a recent number of the Transactions of the American Geophysical Union, BRYAN asked members to contribute reprints and books dealing with oceanography. I would like to repeat that request and to assure you that all donations will be appreciated. Funds have been allocated to purchase various publications, but it will not be possible to subscribe to all journals which include pertinent articles.

Conclusion

Next year I hope to be able to give a more detailed account of actual accomplishments, rather than a résumé of policies and plans. However, I believe you will agree with me that the future of oceanography in the United States is very bright, and that the Hydrographic Office can contribute materially to its development.

Hydrographic Office,
U. S. Navy Department,
Washington, D. C.

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FURTHER REQUIREMENTS IN OCEANOGRAPHIC RESEARCH FOR NAVAL ORDNANCE APPLICATIONS

L. H. Rumbaugh

It is believed that the Section on Oceanography of the American Geophysical Union will be interested in a résumé of the Naval Ordnance Laboratory and Bureau of Ordnance oceanographic work during World War II and in an outline of their future requirements for oceanographic research.

The Naval Ordnance Laboratory (NOL) is a Bureau of Ordnance activity engaged in research and development of a wide variety of weapons, counterweapons, and ordnance materials. A major fraction of this work is concerned with underwater weapons and warfare. Since a knowledge of the environment in which a weapon is to be used is essential for both proper design and intelligent use, the subject of oceanography in its broadest sense has many important ordnance applications. In fact, the field of interest includes a majority of the physical, biological, and chemical factors which describe oceans and their land and air borders. It follows that the Navy's activities in ordnance have contributed and will continue to contribute importantly to basic and applied research in oceanography and allied sciences such as marine biology, geophysics, and terrestrial magnetism, both through active participation and by financial support.

Recent ordnance work in oceanographic and related sciences

Wartime research was directed primarily to investigations having immediate applications. This work ranged from numerous small-scale projects to programs of a magnitude beyond the resources of most private institutions.

Wind, sea, and swell--The Bureau and the Laboratory were particularly active in this field. Observations were carried out at numerous coastal and island locations, including Cape Henry, Yakina Head, Ambrose Channel, and Point Reyes Beach in the United States; Morro Point, Puerto Rico; and Kahului, Mokapu Peninsula, and Kileauea Point in the Hawaiian Islands. Analyses of these data by the Laboratory were supplemented by statistical analyses of samples of large masses of unanalyzed data from the Hydrographic Office and other sources, through contracts with the American Museum of Natural History. These studies and numerous contributions by others (Beach Erosion Board, Coast Guard, Bureau of Ships, British Admiralty, etc.) established reasonably reliable correlations between such variables as wind velocity and direction, fetch, offshore depths, and the heights and periods of waves, and allowed conditions in Japanese home waters to be predicted with considerable confidence.

Acoustic and seismic investigations--Emphasis on acoustic devices for mines, torpedoes, and antisubmarine weapons in the War led the Bureau and the Laboratory to extensive studies of acoustic background noise, sound propagation, bottom impedance, and underwater phenomena connected with explosions. These studies were pursued at a number of stations in our coastal waters, in the Caribbean, and in the Pacific. In addition, the Naval Ordnance Laboratory participated in a number of cooperative expeditions; for example, equipment and men were contributed to the Saluda cruise in coöperation with Woods Hole Oceanographic Institution, in which underwater seismic studies and the first tests of long distance propagation of sound in the minimum velocity layer at about 600 fathoms were carried out under MAURICE EWING'S direction. A related NOL project of considerable interest to ocean island geologists is the present program to obtain a seismic profile of Bikini Atoll in preparation for the atomic bomb tests.

Marine biology--Two important contributions have been made in this field by the NOL. One was an extensive study of the bathymetric, seasonal, and geographic distributions of fouling organisms, including an investigation of fouling near the bottom at depths down to 30 fathoms. The second was the study and identification of both known and new noise-making fishes and other marine life forms by quantitative acoustical methods. This work was carried out in waters of the Atlantic Coast in cooperation with the United States Fish and Wild Life Service, and as a Navy

activity in an expedition extending from the Hawaiian Islands to Guadalcanal. Our own studies have recently been supplemented by over 80 recordings obtained by C. J. FISH from the Japanese.

Terrestrial magnetism--Under contracts with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, and through the cooperation of the United States Coast and Geodetic Survey and the Hydrographic Office, complete new magnetic maps of the horizontal and vertical components of the Earth's field were prepared for all oceans, and studies of the short-time fluctuations of the Earth's magnetic field were carried out. This work involved the establishment of magnetic observation stations in the West Indies, South America, and Alaska, together with observations at existing stations in such other areas as were accessible to the Allied Nations.

Airborne magnetometers and other magnetic instruments--On 1 June 1946, the United States Navy released information on various airborne magnetometers. A continuously recording magnetometer was developed jointly by the Naval Ordnance Laboratory and the Bell Telephone Laboratories as a U-boat detector for the Bureau of Ordnance and the Bureau of Aeronautics. It has been further developed and combined with navigational and mapping devices by the Naval Ordnance Laboratory, and has been used for two years by the United States Geological Survey and the Naval Petroleum Reserves to prepare total field maps of extensive areas with accuracies of about two gammas. This development also is of interest to oceanographers and submarine geologists as an airborne or waterborne method for studying the basement structures of submarine trenches and ridges, atolls, arc-forming islands, volcanoes, and continental shelves.

The importance of magnetic mines, degaussing, and ordnance recovery has led to remarkable developments in portable magnetic instruments of electronic types, capable of continuous recording at precisions as high as one gamma.

Miscellaneous studies--A wide variety of miscellaneous studies were made on tides, currents, and ocean bottoms in relation to the stability of mines; drift observations were made on floating objects; studies were conducted in the transparency of sea water; corrosion and endurance studies were carried out, etc.

Instrumentation and engineering--Wartime ordnance developments have led to many improved or new instruments and devices of considerable importance to the oceanographer. Among the advances in underwater acoustic instrumentation, for example, are new measuring instruments with accuracies approaching two db over a considerable range of frequencies, marked improvements in acoustic standards and calibration, a portable inexpensive continuously-recording fathometer, and a new type of wave and swell recorder.

Miscellaneous devices of interest include portable recorders of high quality suitable for use in ships and boats at sea, underwater position indicators of the "Here-I-Am" type, salinity meters, underwater cameras and illuminants, electrical depth gauges, etc. In addition, many improvements in techniques and materials for underwater work have resulted from experience with extensive underwater installations, new types of ordnance, and test procedures under service conditions.

The above summary of oceanographic activities for ordnance applications is necessarily brief and incomplete. Practically all of the research information can be published as rapidly as appropriate authors care to prepare and submit articles for publication, so most of the important details should appear in technical journals within the next year or two.

Future research requirements

Work during the War is illustrative of future requirements for research in oceanography for Navy applications, with the important difference that peacetime emphasis should be shifted toward an integrated program in basic research.

The items of special ordnance interest in such a program would include the geographic, seasonal, and bathymetric factors describing sea, winds, and swells; tides and currents; weather conditions; water and air temperatures; visibility and transparency; geology of shore lines, continental shelves, and islands; sedimentation and character of the bottom; precipitation; disturbances of seismic, magnetic, or electrical origin; acoustic transmission in water and bottom; marine noise; salinity and corrosion; fouling organisms and fungi. The Western Pacific and Arctic waters are areas of special interest, since little is known of these regions. In other words, most of oceanography and its allied sciences are of interest to naval ordnance, and the rest probably would be included in overlapping lists from other Navy activities. This statement is rather obvious, since the ocean is the medium in and over which the Navy operates.

An integrated program in basic oceanographic research would supply source material to meet practically all of the Navy's requirements. Such a program, given proper support in the twenty or more government and private agencies interested in oceanography, could be coordinated from the newly formed Oceanographic Division of the Hydrographic Office. Peacetime research can avoid the lavish expenditure of money and personnel, the duplication of effort, and the exclusion from vital areas which characterize wartime research in oceanography. In addition, most of the secrecy surrounding last-minute frantic research, to safeguard new weapons or impending operations in time of war, would not be necessary in a broad peacetime research program. It probably is important to emphasize the last point, since the Armed Forces often are erroneously accused of unnecessary secrecy when in fact both the Army and Navy freely publish most of their peacetime research, in addition to contributing to many important engineering and technological advances.

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THE OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN 1945 AND PLANS FOR 1946

J. F. Farley

Before the War the oceanographic work of the United States Coast Guard was largely that undertaken in connection with the operation of the International Ice Patrol. During the war years the shortage of vessels and trained personnel curtailed the Coast Guard's oceanographic activity. Its interest in oceanography has continued, however, and the increased air traffic over ocean areas has added oceanographic problems in air-sea rescue. Beginning with this season the International Ice Patrol has been resumed, and it is expected that by 1947 an active oceanographic program again will be made a part of Ice Patrol.

Bathythermograph slides are being taken by the ships of the Weather Patrol and Ice Patrol to develop additional information on such problems as diurnal warming, variation in the depth of the mixed surface layer, internal waves, and vertical temperature sections across major currents. From merchant ship reports the Ice Patrol vessels are preparing surface isothermal charts of the Grand Banks region every two weeks. No dynamic topographic surveys of the Grand Banks or Labrador Sea areas can be made by the International Ice Patrol during this season, but it is expected that this type of work, together with experimental work on new instruments and methods, may go forward in 1947. Meanwhile, the Coast Guard is represented in the Crossroads project by the loan of oceanographic personnel and equipment.

U. S. Coast Guard,
Washington, D. C.

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OCEANOGRAPHIC ACTIVITIES OF THE COAST AND GEODETIC SURVEY

Leo Otis Colbert

The activities of the United States Coast and Geodetic Survey in oceanography have for five years been almost exclusively directed toward furnishing the Armed Forces with information in areas of strategic importance. Because of the confidential nature of much of this work, it was not possible during the War to present to the Section of Oceanography more than a general outline of the work. Now that the need for secrecy has passed, I shall review the hydrographic accomplishments of past years and point out some of the uses of surveying equipment for war purposes.

West Indies Bases--The defenses of the Western Hemisphere, particularly the eastern approaches to the Panama Canal, were potentially strengthened when sites for naval bases in the West Indies were leased from Great Britain in partial exchange for fifty over-age destroyers. Before the bases could be activated, it was first necessary to make detailed hydrographic and topographic surveys.

In October 1940, the Coast and Geodetic Survey had four completely equipped and fully-manned survey ships, with highly trained officer personnel executing hydrographic and other surveys off the Atlantic and Gulf coasts of the United States. These ships were immediately alerted, and the commanding officers ordered to be ready to proceed to the West Indies.

Necessary diplomatic arrangements were made between the State Department and British officials, and early in November these four survey ships received confidential dispatch orders to proceed, under radio silence, to the West Indies. All ships sailed the same day and arrived at Trinidad, Mayaguana, Antigua, and Jamaica before the local authorities had received confirmation from their home government that the bases had been leased. State Department officials in these islands had been advised that the expedition was en route, and made arrangements for the Coast and Geodetic Survey ships to carry out their assignments. The work was started immediately and continued without interruption.

The surveys at Trinidad were accomplished by January 15, 1941, and advance tracings of parts of this work were furnished on that date to construction officers at that base. During February, the surveys of the bases at Mayaguana and Antigua were completed. Early in March, survey work on the base at Jamaica was finished. These surveys included Coast Pilot investigations, descriptive reports of the geographic conditions, and weather and other data on the physical aspects. This Coast and Geodetic Survey expedition to the West Indies, in the remarkably short period of four months, had executed detailed hydrographic, topographic, and tidal surveys of all the bases, and had furnished the complete material to the Armed Forces.

Atlantic coast--Following their return to the United States, three of these survey ships proceeded to the coast of Maine and began a comprehensive survey in the vicinity of Portland. Previous surveys in these waters dated back to the years immediately following the Civil War, 1866-1869. Re-surveys had been made in places of commercial importance, to meet the needs of modern deep-draft vessels, but in other places the old surveys had been considered adequate for local use.

Anchorages were needed along this coast for patrol craft and for the fleet assigned to duty as escort for supply ships and transports. Casco Bay was one of the natural selections for the purpose. It was well known to us that because of their geologic formation these bays had many sunken ledges and boulders which early survey methods had failed to locate, and consequently these rocky bottom formations were serious hazards to any ship with draft deeper than 18 to 25 or 30 feet. Wire drag and detailed hydrographic examinations were made. Within the immediate area of Casco Bay over 50 sunken ledges, boulders, and pinnacle rocks were found. The charting of these obstructions and the removal of a few critical ones made the entire area available as a fleet anchorage. Surveys were continued along the coast through the following years and are in progress during the present season.

In 1941 the Bureau was called upon to survey and establish a new submarine trial course. This was in preparation for the tests and trials of the submarines which we were building and which were later to accomplish so much in the successful conclusion of the War by the blockade of Japan. This project, about 45 miles off the coast of Block Island, involved three operations: First, it was necessary to establish control in the area and mark the course. This involved making a tie at a buoy near the limit of visibility of shore objects, and executing a taut-wire sun-azimuth buoy traverse to and around the submarine trial course; second, a system of closely-spaced lines of hydrography was executed over the area. The position of the ship was controlled by three-point fixes on buoys during clear weather, or by fixes from sono-radio-buoys during fog or haze; and finally, the area of over one hundred square miles was wire dragged to depths between 225 and 350 feet. During the progress of this survey a large number of serial temperature and salinity observations were recorded, and bottom specimens were obtained throughout the area. The course was fixed by a marker buoy, and the Coast Guard set a lighted buoy at this location. For some offshore areas in which a close oceanographic investigation is desired, the above survey methods are particularly applicable.

Other hydrographic surveys were executed for the Armed Forces along the Atlantic coast and the Gulf of Mexico for locating speed trial courses and torpedo ranges, for practice-landing operations, and for locating and charting sunken wrecks.

Tides and currents--The tremendous increase of activities in the Nation occasioned by the War increased very greatly the demands made upon the Coast and Geodetic Survey for information regarding tides, currents, and related phenomena.

In the early days of arming, tidal datum planes and information pertaining to storm tides were required in connection with the construction of harbor installations, coastal defenses, factories, shipbuilding plants, and housing developments. From data accumulated through tide observations, tied in with thousands of bench marks established along our Atlantic, Gulf, and Pacific coasts, the Bureau was prepared to meet the urgent requests for such information.

The currents in our harbors and waterways are important factors in connection with shipping and defensive underwater installations. At a number of places special current surveys were made to determine the characteristics of the local currents, the results analyzed and reports prepared by the Bureau.

Temperature and density observation of the water have been made at our tide stations. The War increased the demand for this information not only because of the increased activities in our harbors but also for use in a variety of underwater military installations and for air-sea rescue work.

Advance information relative to the rise and fall of the tide and the speed and direction of the current played an important part throughout the War. The launching of ships, dependent on the stage of the tide, had to be planned long in advance. The sailing schedules of large ships had to be arranged so as to leave and arrive at high water slack. In carrying the War to foreign shores, tide and current predictions were indispensable in connection with training and combat operations of the various branches of our Armed Forces. For amphibious operations they supplied essential data for navigation and landing operations. In aerial operations a knowledge of the stage of the tide was of immense value in target identification by both visual and radar methods. This was especially true in the Pacific where the tide often changes the appearance of small islands, and where targets were often located near the coastline.

The information required for these activities was made available by various means: (1) By expanding the regular tide and current tables. Not only were new reference stations and greater coverage included in each issue, but also many thousands of additional copies were printed; (2) by publication of special tide and current tables. Because of the complexity of the tide in the Pacific and the need for tide predictions for remote places, the Coast and Geodetic Survey issued special tide and current tables for a number of areas in the Pacific theater. Among the areas covered by such tables were the Aleutian and Kuril Islands, the Japanese mandated islands, Malacca Strait, the Philippine Islands, Japan, and China; (3) by prediction of tides and currents for special purposes. In addition to the published tables many special predictions of tides and currents were prepared for use in confidential reports compiled for the several branches of the Armed Forces as well as to meet specific requests of various agencies. Information was thus supplied for such activities as the launching of battleships, naval speed trials, advance bases, training schools, operations of the Army Air Forces, construction projects of the United States Engineers, and hydrographic surveys; (4) by the issuance of predicted tide curves to supply more detailed information for landing operations. The curves showed graphically the rise and fall of the tide to a scale which would permit the height to be determined for any time of the day; (5) by tide and light diagrams; and (6) by detailed reports for specified areas.

In 1942 the Director of Weather, United States Army Air Forces, requested the Coast and Geodetic Survey to furnish his office with tide and current information for various areas throughout the world. Detailed information was collected and correlated from source materials in our files, from captured enemy documents, and from various libraries. Translations were made from Japanese, German, French, Russian, Dutch, and other foreign nautical and scientific publications. This information was furnished in the form of reports dealing with specified areas.

In 1943 the Hydrographic Office of the Navy was designated by the Joint Chiefs of Staff as the agency supplanting the Director of Weather, Army Air Forces in furnishing all oceanographic information to the Armed Forces, and thereafter that office allocated funds to the Coast and Geodetic Survey for the continuation of the work. In all, 68 reports covering the various combat areas in the European and Pacific theaters of war were prepared.

As these reports were used for both planning and conducting amphibious operations, they required the fullest information available for the different areas, with detail for even obscure beaches. They contained the following material: (1) A brief characterization of the tides and currents in the area, with notation of any unusual features such as swells, seiches, or tidal bores; (2) table of tidal constants and differences with explanation and examples for using the data; (3) graphs showing typical tide curves for all types of tide in the area, which permitted ready determination of the height of the tide at any time or the changing height during any desired period of time; (4) daily tide prediction for the reference station or stations best suited for the area; (5) tide and light diagrams; (6) detailed descriptions of tidal and other currents affecting navigation, particularly in passages near shore; (7) daily current predictions for important passages whenever possible; (8) index charts showing the location of each place for which tide and current information was given; and (9) bibliography, giving source or authority from which information was obtained.

Pacific Coast--Up to the date of October 1941, Coast and Geodetic Survey vessels in Alaska had completed charting a large percentage of the waters of southeastern Alaska and had made excellent progress in charting southwestern Alaska. The charting of waters in the Aleutians had progressed from the vicinity of Unimak Pass to the Islands of the Four Mountains.

After the close of the Alaskan season of that year, the Coast and Geodetic Survey ship Explorer sailed from Seattle for Midway and ran a line of soundings en route. A project in the vicinity of Midway was completed on December 3, 1941, and the Explorer proceeded toward Johnston Island on a hydrographic investigation. The Japanese attack on Pearl Harbor occurred while the ship was at sea and the War caused the abandonment of further observations. The Explorer returned to Seattle, where this vessel and the remaining Pacific Coast survey vessels were armed and outfitted for charting in the defense zones of our coastal waters.

All Pacific Coast survey ships were engaged during the War in making charts along the Aleutian chain, between Dutch Harbor and the west coast of Attu. The survey ship Derickson was acquired in 1944 and joined the Explorer, Surveyor, E. Lester Jones, and Patton in this work. Charts resulting from these surveys covered all main harbors, approaches, and anchorages in this area.

Philippines--At the outbreak of the War the Coast and Geodetic Survey had completed 40 years of survey and oceanographic work in the waters of the Philippines. Because of the great variety of conditions of shoal waters and ocean deeps, of barrier coral reefs and natural clear channels, and of other submarine features, it is considered that the oceanographic work performed by the Bureau has been unsurpassed in any similar world region. The charts based on these surveys show in great detail the character of these waters. This is in distinct contrast with the vast area between Midway and the Philippines where there were, in general, only very poor charts processed from sketchy surveys.

The descriptive reports of the physical features submitted by field parties over this period were extremely valuable to a number of war agencies working in specialized fields. In addition to the tremendous advantage to our forces of having accurate navigation charts of this region, the detailed surveys provided excellent source material from which were constructed 537 special large-scale quadrangles for the use of the Army in planning and executing the invasion of the Philippine Islands. They were also the origin of 38 bombardment charts of critical areas in the Philippines.

New equipment--The Bureau made investigations during the War with sonar, reflecting radar, and loran, for possible use in surveying. Sonar, designed originally for detecting submarines, proved useful in locating shoals and wrecks. Reflecting radar and loran are excellent navigation equipment but are not sufficiently accurate for hydrographic surveying.

In 1935 Coast and Geodetic Survey ships made extensive tests of the velocity of sound in sea water off the California coast. During these tests TNT bombs were fired at depths up to 800 fathoms, and sound waves resulting from the deep-sea explosions traveled forty miles to hydrophones set at about 800 fathoms. This met the needs of the Bureau at the time, and no further development was attempted. It has been of great interest to the Bureau to learn of the recent experiments made by the Woods Hole Oceanographic Institute in the transmission of sound over great distances and the successful development of Sofar.

The Coast and Geodetic Survey ship Explorer was used to make hydrographic survey experiments with shoran equipment off the coast of Attu, Alaska, during August and September 1945. Shoran had previously been used by the Army Air Forces for precision bombing. The equipment for hydrographic surveying is essentially the same as that used for bombing and consists of two accurately-located shore stations and a shoran station installed on a ship instead of a plane. The ship equipment, in effect, measures distances, instantaneously, to the shore stations. The tests were very successful, and during 1946 it is planned to make hydrographic surveys with shoran in Alaska and off the Atlantic coast. The effective range of this device is 30 per cent more than the line of sight distance.

The British system of position finding, called Decca, has been investigated by this Bureau, and further tests are contemplated because of the excellent possibilities of this equipment.

A new electronic instrument, called the radio-ranger, has been designed in the experimental laboratory of the Coast and Geodetic Survey. The primary equipment consists of two shore stations and a ship station. Preliminary tests indicate that the radio-ranger may be used to extend accurate ship hydrography as far as three hundred miles off the coast.

It is my belief that developments in the field of electronics will be used in the near future to a great extent in oceanographic work, because means will be provided through the use of such devices for locating the position of the surveying or investigating ship with desirable accuracy.

U. S. Coast and Geodetic Survey,
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RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1945 TO APRIL 1946

H. U. Sverdrup and Staff

(Contributions from the Scripps Institution of Oceanography, New Series, No. 281)

The present report deals not only with the activities in 1945-46, but opportunity is also taken to review briefly the oceanographic studies at the Scripps Institution during the years of war. These studies fall mainly within four subjects: Examination of the surface layers of the ocean in connection with the submarine warfare; studies of the boundary layer atmosphere-ocean; studies of sea, swell, and surf; and studies of beaches in relation to wave action.

The surface layers of the Western Pacific--This work was primarily directed towards compilations of existing information for the use of submarines or anti-submarine vessels. In preparing these compilations it was often necessary to carry out interpolations and extrapolations because of the few available data, but on the whole the work was of such a nature that it did not lead to any new contributions to our understanding of the regions. During the last year it has, however, been possible to undertake detailed studies of the oceanographic conditions around the islands of Japan, making use of the numerous observations which had been taken by Japanese organizations prior to 1939. As an example of these studies, J. C. ARMSTRONG has prepared a report entitled "The oceanography of the Kii Suido," which will be published in a later issue of the Transactions. In this and other cases, the published studies by Japanese oceanographers were inadequate, but it was possible to derive considerably more information from their observations than they had extracted. Other areas have been examined in a similar manner and the results will probably be published later.

Boundary layer problems--The examination of the boundary layer problems has dealt with conditions in the atmosphere and in the ocean. When dealing with the atmosphere it has been established that the coefficients of eddy conductivity and eddy diffusivity which apply at indifferent equilibrium are also applicable under unstable conditions, that is, when the air is much colder than the water. Furthermore, it has been found that simple laws are applicable at wind velocities exceeding six meters per second [SVERDRUP, 1946]. These conclusions have been used by C. J. BURKE [1945] for a discussion of the transformation of polar continental to polar maritime air and for the preparation of graphs by means of which the air temperature near the sea surface at different distances from the coast can be forecast if the lapse rate in the outflowing polar air is known. Comparison with observed values has given satisfactory results.

When dealing with the boundary layer in the ocean, J. C. ARMSTRONG [1946] has examined the characteristics of the surface layer when cold air flows over the water and has shown that under these conditions static instability is maintained in the sea with temperature slightly increasing and salinity slightly decreasing with depth. In order to account for the observed conditions it was necessary to introduce a coefficient of eddy diffusivity (of salt) much smaller than the coefficient of eddy conductivity (of heat).

A systematic study has been started of the distribution of temperature in the surface layers under different meteorological conditions, making use of bathythermograph observations from weather ships. As yet, only preliminary reports on the findings have been prepared.

In all these studies monthly charts of sea-surface temperatures and currents have been helpful. These were prepared in 1942 to 1944. At present, an investigation is in progress dealing with the proper interpretation of vector averages used in presentations of currents.

Sea, swell, and surf--In the summer of 1943, H. U. SVERDRUP and W. H. MUNK [1946] carried out a theoretical study of the growth of waves under the influence of the wind. This study has been revised in the spring of 1946 and has been submitted to the Hydrographic Office for publication. Definite relations are established between wind, fetch, and duration on the one hand, and wave characteristics on the other hand, which have been used extensively during the war for forecasting sea and swell on the basis of weather maps from ocean areas. During the war about two hundred weather officers of the Army and Navy obtained special training at the Scripps Institution in the use of these methods.

A great deal of work was devoted to the study of the transformation of waves as they travel from deep to shallow water and to the relation between swell and surf. The studies covered such subjects as the velocity of progress in shallow water, the effect of shoaling bottom in the bending of waves (refraction), height of breaker in relation to height of swell, and relation between height of breaker and depth of breaking. An example of these studies is contained in a paper by R. S. ARTHUR [1946] on refraction around a circular island. It is expected that several other studies will be published in the near future. A number of the results as to waves in shallow water obtained at Woods Hole, the Department of Mechanical Engineering at the University of California at Berkeley, and at the Scripps Institution were applied to the problem of depth determination by means of aerial photographs of waves and to other problems in amphibious warfare.

Beaches in relation to wave action--A number of systematic measurements of beach profiles and studies of sand movement have been undertaken in localities where the characteristics of the surf have been studied simultaneously. Results have been incorporated in reports with bearing on problems encountered in landing operations, but as yet no scientific papers have been published.

Under other activities carried out in connection with war research it may be mentioned that during the spring of 1946, the Utility Squadron 7 of Fleet Air West Coast has taken a series of photographs of dye bombs in order to examine the rapidity with which the colored area spreads as a result of processes of diffusion. The experiments show that these processes are extremely irregular, but they also indicate that the "diffusion coefficient" which can be introduced is proportional to the dimensions of the diffusing area. These studies led to some of the theoretical work reported by G. F. McEWEN [1945].

McEWEN has checked the tables of the integrals mentioned in the report for last year under (D) and has completed the tabulation of the integrals which were mentioned in that report as needing tabulation. He resumed work on the problem of diffusion from an instantaneous circular area source for a constant coefficient of diffusion. A general solution was worked out involving $\int_{y_1}^{y_2} e^{-b^2x^2} I_1(x)dx$, which can be evaluated to any required degree of accuracy by means of a series derived by repeated integration by parts. Numerical applications of this series solution required the computation of tables of $e^{-x}I_n(x) = f_n(x)$, whose values are between 0 and 1 for all values of x. This involved a good deal of computation even though full use of available tabulations was made. The intervals of x are 0.01 for $x<0.2$, 0.1 for $0.2\leq x\leq 6$, and 0.5 for $6<x\leq 20$ in this basic table which has a variety of uses. Therefore, an accuracy to 10^{-7} was attempted in computing the values of $f_n(x)$ even though the requirements of immediate oceanographic applications would be met by rough approximations. An approximate method was also worked out to facilitate applications not requiring great accuracy.

Results of certain observations at sea suggested assuming the diffusion coefficient to be proportional to the distance from the center. Also forthcoming researches required the solution of the problem of vertical diffusion from a layer of indefinite extent and given thickness, assuming the coefficient of diffusion to be proportional to the distance below the surface.

A general solution of each of these problems was worked out and found to depend upon the same $f_n(x)$ function. Moreover, this function arises in other physical problems, including that of random migration considered at length by KARL PEARSON in 1906, and that of heat transfer to a liquid flowing through a tube. Accordingly, the large amount of time devoted to researches on the integral mentioned above and to the computation of a table of values of $f_n(x)$ appear to be justified.

A paper now in press on "The reality of regularities indicated in sequences of observations" was presented by McEWEN at the Symposium on Mathematical Statistics and Probability held in the University of California at Berkeley during August 13-18, 1945.

The usual observations of temperature, salinity, and weather at our shore stations have continued, but the supplementary observations from the United States Lighthouse Tender were terminated in December, 1944. There were about 1800 salinity and temperature observations, and 1500 wind observations. Barograph and pyrheliometer records and daily observations of humidity and temperature were continued. Results of the 1941 cruise of the E. W. Scripps have been prepared for publication.

This work represents results of research carried out for the Hydrographic Office and the Bureau of Ships of the Navy Department under contract with the University of California.

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POSTWAR PLANS OF OCEANOGRAPHIC LABORATORIES, UNIVERSITY OF WASHINGTON

P. E. Church

After curtailed activities during the War because of war service of some staff members, unavailability of finances for research, loss of graduate students, sale of M. S. Catalyst to the United States Coast Guard, and temporary occupation of the Friday Harbor campus by the Coast Guard, the present staff of the Oceanographic Laboratories is planning a reactivation program.

The field laboratory at Friday Harbor has been returned to the University, and the buildings are now being reconverted for scientific use. The oceanography laboratory building on the Seattle campus was under a Navy contract which expired on June 30, 1946. Occupation of this building by the Navy has retarded the return to normal of the scientific work of the Oceanographic Laboratories. The new biennial budget, now in process, will take into consideration the various financial demands necessary for placing the Laboratories on a sound working basis. All indications are that the budget requests will be favorably received.

The research activities of the Oceanographic Laboratories will include investigations indicated by the following: (1) Radioactivity of sea water and marine deposits; (2) interaction of the atmosphere and ocean; (3) bathythermograph soundings; (4) general hydrography of Washington sea waters; (5) characteristics of submarine canyons off the coast of Washington; (6) dynamic oceanography; (7) general chemical and physical characteristics of sea water of Puget Sound, Bering Sea, and North Pacific areas; (8) certain other specific chemical problems including; (a) distribution of various nutrient salts, (b) refinement of methods of determination of the constituents of sea water, (c) role of strontium in the sea and in marine organisms, (d) analysis of certain marine deposits and products, and (e) the chemical utilization of marine products; (9) biochemistry of marine organisms; (10) biochemical and ecological studies on marine microorganisms.

During the War, the staff of biological scientists suffered casualties. Retirement, death, and resignation took a toll of six. Staff members are being added to rectify this situation as rapidly as possible, and as staff members are added in the various fields of marine biology, the scope of activities will be enlarged.

The loss of the M. S. Catalyst is a severe handicap, but it is hoped that a surplus naval vessel will be made available and refitted for scientific purposes. The staff anticipates obtaining a vessel large enough to do work in the open sea all year round.

One of the requests in the budget is for ample finances to bring visiting noteworthy scientists to Seattle and the field laboratories at Friday Harbor.

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DISCUSSION OF

"STEAM FOG OVER LAKE MICHIGAN IN WINTER" by P. E. CHURCH

[Trans., v. 26, pp. 353-357, 1945]

DAVID H. MILLER (War Department, Washington, D. C., March 18, 1946)--Formation of steam fog depends upon the rate of transfer of water vapor at two levels, namely, (1) at the surface of the water, where water vapor is introduced into the lowest layer of the atmosphere, and (2) at the top of the potentially foggy layer, where vapor is removed from the lower air by mixing with drier air aloft. At the former level, transfer is a function of temperature of the water, dewpoint, and the turbulent exchange; at the latter level it is a function of the vapor pressure and turbulent exchange in the air.

These rates of transfer depend on four factors, the balance among which determines whether the lower layers of air become saturated and excess water condenses as fog-droplets: (a) The difference between vapor pressures at the water surface and in the lowest layer of air; (b) the difference between vapor pressures in the potentially foggy layer of air and the higher layers; (c) turbulent exchange just above the water surface, and (d) turbulent exchange at higher levels. Introduction of water vapor into the potentially foggy layer depends upon (a) and (c), and its removal upon (b) and (d). The relations among these four factors may be seen when they are brought together into an inequality which must be realized if fog is to be formed.

Assume two horizontal planes, one just above the water surface at the bottom of the potentially foggy layer, and the other at its top. It is clear that fog can be formed in previously clear air only if the upward flux of water vapor through the lower plane exceeds that through the upper one. The net upward flux of water through unit-area in a horizontal plane may be expressed as $-A(\partial q/\partial z)$ where A is the Austausch coefficient and q is specific humidity [HEWSON and LONGLEY, 1944]. If the subscript ℓ is used to designate the lower plane and t the upper one, the inequality (1) defines the condition in which more water vapor is added to the air between the two planes than is removed from it.

$$A_\ell(\partial q/\partial z)_\ell > A_t(\partial q/\partial z)_t \text{ . . . . } (1)$$

This inequality can be restated in the more useful form as in (2).

$$(\partial q/\partial z)_\ell/(\partial q/dz)_t > A_t/A_\ell \text{ . . . . } (2)$$

That is, the ratio of the humidity gradients must be greater than the inverse ratio of the eddy conductivity. If these two ratios are equal, there is no change with time in the water content, either as vapor or as liquid, of the air between the two planes. If the left-hand ratio of the inequality is smaller than the right-hand, water vapor will be removed from the layer, and if fog is already present it will be dissipated.

The left-hand ratio is usually a positive number greater than unity, because its numerator, which represents the humidity gradient near the water surface, is normally much larger than its denominator, which represents the humidity gradient at the top of the potentially foggy layer.

The right-hand term also is likely to be greater than unity, however, because of the general increase of eddy conductivity with height. A_ℓ is always small, because of proximity to the water surface, so that under all conditions, except when an inversion is present at the height represented by the subscript t, it is far exceeded by A_t.

Inequality (2) shows that the vertical gradient of turbulent exchange is fully as important as the difference in vapor pressure between the water surface and the air. A low value of turbulent exchange at the top of the potentially foggy layer--the numerator of the right-hand term in (2)--seems almost essential to the formation of steam fog, except when the left-hand ratio is extremely large; for example, over a kettle of boiling water. In nature, this ratio may be very large when very cold air blows over fairly warm water.

The usual reason for a low value of the right-hand ratio in (2) is the presence of a temperature inversion at the top of the potentially foggy layer. Such an inversion hinders vertical motion, which, if permitted, would in most instances dissipate any fog present by mixing it with a large volume of the dry air aloft. Instability is produced in the foggy air by heating at the bottom, both by conduction of heat from the water and by condensation of water vapor, and in the absence of an inversion aloft the intensification of turbulence upward would soon destroy the fog just formed. The addition of heat at the bottom of the air may steepen the lapse rate sufficiently to destroy a weak inversion below which fog has already formed, and thus eventually lead to the dissipation of the fog.

Data are not available for the full evaluation of inequality (2), but an approximation will be made as an example. Table 1 presents reasonable values of humidity gradient and eddy conductivity in two layers of air, each one meter thick, above a water surface, at the top and at the bottom of a zone seven meters in depth.

Table 1--Humidity gradients and eddy conductivity in a layer of steam fog[a]

Height	Vapor pressure	Specific humidity	$(\partial q/\partial z)$	Eddy conductivity
meter	mb	$g\ kg^{-1}$	$g\ kg^{-1} m^{-1}$	$g\ cm^{-1} sec^{-1}$
7	2.5	1.8		
			0.3	3.20
6	3.0	2.1		
1	5.0	3.2		
			1.4	0.23
Surface	7.5	4.6		

[a] The values of vapor pressure in Table 1 were interpolated between the value at the water surface (temperature 3°C) and the value at seven meters, from representative observations given by CHURCH. The values of eddy conductivity are derived from the approximate equation $A = 1.45 \times 10^{-4} u_1 z^{(n-1)/n}$, the eddy conductivity of the air over a smooth snow surface [SVERDRUP, 1936, p. 42]. The value assumed for u_1, the wind speed at one cm height, is 100 cm sec^{-1}, but this numerical value does not affect the results, since only the ratio between the two values of eddy conductivity is desired; the value of n is taken as 6 at the upper level, 4 at the lower [SVERDRUP, 1936, p. 14].

If the values in the last two columns of Table 1 are substituted in inequality (2), the ratios become, respectively, 1.4/0.3 and 3.20/0.23, or 4.7 and 13.9. The inequality is not true, and fog will not be formed.

If, however, an inversion is present at the upper level, the value of the eddy conductivity at this level will drop to 1.00 or less [SVERDRUP, 1933], and the right-hand term will decrease to 4.3; this is less than the value of the left-hand term (4.7), and the formation of steam fog is possible.

CHURCH'S description of flat tops on layers of fog suggests the presence of inversions, which are likely to exist in air that has had a trajectory over a cold snow-covered land surface. Steam-fog may be regarded as an occasional, visible phenomenon associated with the early stages of transformation of cP air into mP by addition of heat and moisture to the air below an inversion. In the later stages of transformation, the inversion is destroyed by heating at the water surface, and the steam-fog is dissipated.

The columns which sometimes break through the top of the fog may be rendered possible by high relative humidity at upper levels. The strato-cumulus deck reported by CHURCH is evidence of high humidity aloft, which would favor the retention of fog droplets in columns of air that break through the inversion from the foggy layer below.

Relative humidity of the lower air is chiefly important in determining how much time is required to raise the dewpoint to the temperature of the air by addition of water vapor; it does not determine whether or not steam fog will form. It may, however, determine whether or not nocturnal fog occurs over streams, as is frequently observed during anticyclonic weather in the fall. In the process of formation of this fog, air is cooled by contact with the cold ground-surface, accumulates in the stream valleys by downslope motion, and is cooled further by radiation; whether or not water vapor is condensed as fog during the period of the night may depend on the initial relative humidity of the air. In this instance, then, relative humidity may be a contributory cause in producing the winding ribbons that can be seen from the air to follow faithfully every meander of the watercourses.

In the light of the above discussion, it is clear why CHURCH found no correlation between the occurrence of steam fog and the meteorological elements ordinarily observed, namely, relative

humidity, air temperature, cloudiness, and wind speed. The quantities that appear in inequality (2) are more elusive than the elements CHURCH observed, but are evidently the critical ones.

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HEWSON, E. W., and LONGLEY, R. W., Meteorology theoretical and applied, New York, Wiley, 1944. [Formula 54.8, p. 156: A is used in this note in place of its equivalent, $K\rho$, where K is eddy diffusivity and ρ is density of the air.]

SVERDRUP, H. U., The eddy conductivity of the air over a smooth snow surface, Geophys. Pub., v. 11, p. 42, Oslo, 1936.

SVERDRUP, H. U., The Norwegian North Polar Expedition with the "Maud," 1918-1925, Scientific Results: Volume 2, Meteorology; Part 1, Discussion, Bergen, 1933. [On p. 66 is a discussion of values of A within inversions; u_1 is again assumed to be 100 cm sec^{-1}.]

WOODROW C. JACOBS (Research and Development Division, Air Weather Service, Washington, D. C., May 11, 1946)--In attempts to relate the critical point at which steam fog is formed over Lake Michigan to such factors as wind speed, T_w, T_a, $(T_w - T_a)$, etc., CHURCH concludes that the principal control is the quantity $(E_w - E_a)$ [for notation, see footnote below].

However, a consideration of the mechanism of fog formation over warm water surfaces suggests the use of $(E_w - E_s)$ rather than $(E_w - E_a)$. While it is true that the rate at which water vapor is conducted into the boundary layer is proportional to $(E_w - E_a)$, it is obvious that values of $(E_w - E_a)$ from very nearly zero to the largest difference observed in nature would be possible without steam fog formation as long as $(E_s - E_a)$ within the lower boundary layer remains sufficiently large. In other words, the critical point at which fog will form must be defined in some manner by both $(E_w - E_a)$ and $(E_s - E_a)$ or, stated in other terms, $(E_w - E_s)$ must be sufficiently large with respect to $(E_w - E_a)$ such that when $(E_s - E_a)$ becomes zero, $(E_w - E_a)$, now identical to $(E_w - E_s)$, is still a sizeable positive quantity.

In the above connection CHURCH states that " . . . steam fog will not be visible until the difference $(E_w - E_a)$ is approximately five mbs." This statement appears to be based on rather inconclusive evidence, since the data show that 12 out of 43 recorded cases of fog occurred with $(E_w - E_a)$ less than five mbs. Also, his statement that "With a vapor pressure difference of more than 5.5 mbs nearly always there were columns that extended upward into the low stratus deck" appears unsubstantiated by the data, since in only four of the 13 cases in which $(E_w - E_a)$ was greater than 5.5 mbs was fog reported as "columnar" while four of the eight cases reported as "columnar" occurred with $(E_w - E_a)$ less than 5.5 mbs.

CHURCH'S statement on page 356 that " . . . this phenomenon is of relatively common occurrence elsewhere at other seasons where the essential condition is met in which a warm, wet surface is contacted by air so cold that its vapor pressure is lower than that of the wet surface" can hardly be considered profound. If this were the only "essential condition," steam fog would be of almost universal daily occurrence over nearly all oceans during all seasons and over large portions of the continents during the warmer seasons. The essential requirement, again, is that $(E_w - E_s)$ be large with respect to $(E_w - E_a)$. However, the writer would not propose to overextend the latter line of reasoning, since with small absolute values for $(E_w - E_s)$ and $(E_w - E_a)$ and with low wind speeds, the radiative transfer of heat may be more important in raising T_a (and thus E_s) than is the transfer of moisture in raising E_a.

In his Figure 1, CHURCH has plotted fog characteristics in relation to T_a and $(E_w - E_a)$ with rather indifferent results. For example, dense fog is reported with $(E_w - E_a)$ as low as 5.23 mbs, while traces are reported with $(E_w - E_a)$ as high as 5.39 mbs. With approximately the same values for T_a, dense fog occurred with $(E_w - E_a)$ as low as 5.42 mbs, and traces at 5.39 mbs.

Notation is according to CHURCH as follows: For temperatures and humidities: T_w, temperature of the lake surface; T_a, air temperature at a height of seven m; E_w, vapor pressure at T_w; E_s, saturation vapor pressure at a height of seven m; and E_a, vapor pressure at a height of seven m. For fog: 1, trace, horizontal coverage less than 0.2 of water surface; 2, patches, horizontal coverage from 0.2 to 0.9 of water surface; 3, moderate, horizontal coverage complete, but water visible from directly above, this type usually not more than five m thick; 4, thick, coverage complete, water not visible from pilot house (15 m), short-scattered columns above top of fog blanket; 5, dense, isolated columns whose diameter is much less than vertical height extend above general layer of fog; and 6, dense-columnar, not defined by CHURCH, but described in the table as dense fog existing in columns, occasionally reaching heights of 200 to 300 ft.

T_a, however, should be a factor determining the critical conditions under which steam fog will form. While it is true that steam fog is theoretically possible at any value for T_a providing the proper moisture and temperature relationships exist within the boundary layer, nevertheless, for a given observed value of $(E_w - E_s)$ there must exist a maximum possible value for $(E_s - E_a)$ for each value of T_a, that is, the lower the temperature, the smaller the maximum possible $(E_s - E_a)$ and the greater the possibility that E_a will become potentially greater than E_s (a state of supersaturation = fog).

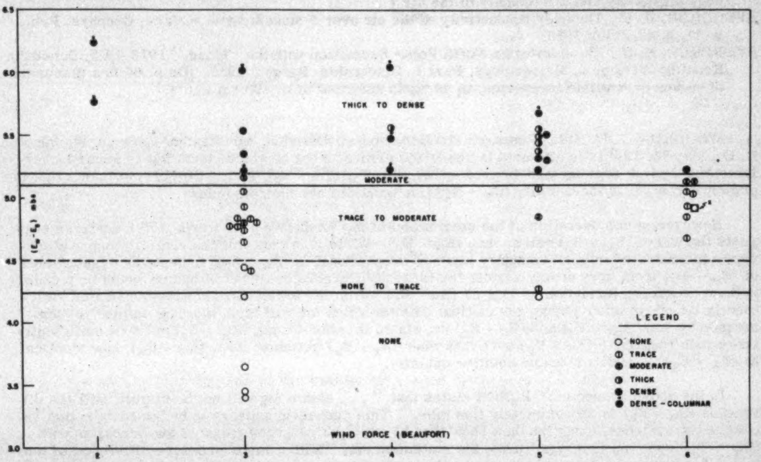

Fig. 1--Critical limits for steam fog of various types in relation to surface wind speed and $(E_w - E_s)$. The critical limits for steam fog formation and the vertical extent of the fog appear to be independent of surface wind speed for observed values of $(E_w - E_s)$. The critical limits which define steam fog of various horizontal densities (distinguished by the classes "none," "traces," "moderate," and "thick-dense-etc.") appear to be given excellently by $(E_w - E_s)$. The only observation falling out of line (marked "x") is assumed to be erroneous.

It has been mentioned that CHURCH has plotted fog characteristic as a function of $(E_w - E_a)$ with only fair results. In Figure 1, the same fog data are plotted, but this time as a function of $(E_w - E_s)$. The agreement is excellent. It will be noted that thick to dense fog occurs only with $(E_w - E_s)$ equal to or greater than 5.2 mbs, and that all observations with $(E_w - E_s)$ greater than this figure present fog within these classifications. The zone within which moderate fog appears is very narrow as might be expected from theory, three of the five cases occurring within the very narrow range for $(E_w - E_s)$ of 5.1 to 5.2 mbs. No cases of moderate fog occurred below 4.8 mbs. The lower critical limit for fog formation (as traces) appears to be 4.25 mbs with a narrow transition zone between this value and 4.5 mbs where traces of fog may or may not occur. There is only one observation that falls out of line on this diagram, that is, one case in which no fog was reported when $(E_w - E_s)$ was 4.92 mbs (marked with "x" in Fig. 1). The writer is inclined to feel that this observation is probably erroneous. At the temperature indicated, a change of only a few tenths in either the wet- or dry-bulb reading would have served to bring this observation into line. The fact that the data plot out as well as they do speaks well for the general quality of the observations.

On page 357 CHURCH mentions the fact that wind speed plays no direct part in the formation of steam fog. This statement appears to be supported by the data given in Figure 1. However, he goes on further to state that the wind speed does control the characteristics of the appearance of the fog after it has formed. An examination of his fog classification given under "Notation" shows that types 1 to 3, and including 4 and 5 as a group, have to deal with the horizontal extent or density of the fog. The distinction between types 4 and 5, (and 6) on the other hand, is made on the basis of the vertical extent of the fog. In his Table 1 he makes a distinction between "dense fog" and "dense fog which occurs in columns." This latter classification might be added as a 6th type, that is, "dense-columnar" and I have so distinguished this type in Figure 1 and Figure 2. In his description, CHURCH states that thick fog occurs only with wind speed less than Beaufort force 3. This must be a typographical error, since all five cases of thick fog reported occurred with wind speed greater than force 3. Similarly, he states that moderate fog occurs only with wind speed less than force 3. This conclusion is not understood, since three of the five cases of moderate fog reported occurred with wind speed greater than force 4 and none with wind speed less than force 3. He also states that dense fog occurs only with wind speed greater than force 3. This statement appears inconclusive since six cases of dense fog occurred with wind speed equal to or less than force 3 against only nine cases with wind speed greater than this value. From the data at hand it would appear that wind speed governs neither the formation nor the characteristics of the fog.

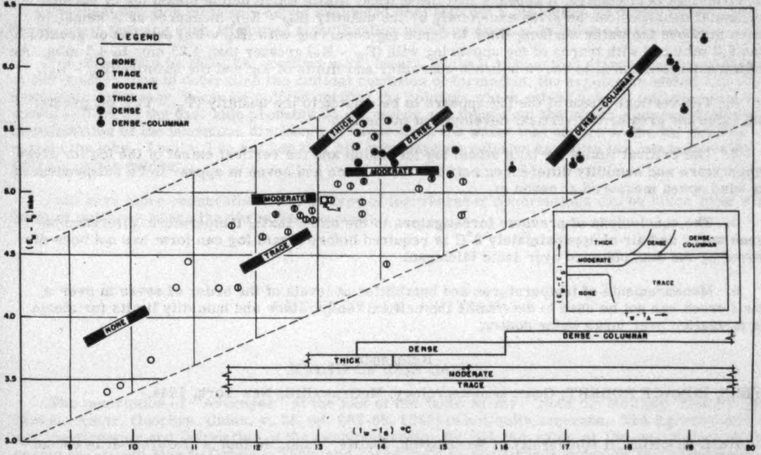

Fig. 2--Critical limits for steam fog formation of various types in relation to $(E_W - E_S)$ and $(T_W - T_a)$. The observation marked "x" is assumed to be in error. It may be noted that the vertical extent of the fog (distinguished by the classes "thick," "dense," and "dense-columnar") appear to be fairly clearly delineated by $(T_W - T_a)$. A distribution similar to that shown by the inset diagram at the lower right has been constructed on the basis of the data given, but the data are insufficient to establish exact limits.

On page 354 CHURCH states "The temperature difference between air and water similarly is not the significant control." Nevertheless, as shown by Figure 2, there appears to be positive evidence that the magnitude of the quantity $(T_W - T_a)$ does have an effect upon the vertical development of the fog. In the upper portion of the diagram it may be noted that the boundaries between "thick and dense" and between "dense and dense columnar" are defined fairly clearly by $(T_W - T_a)$. However, the writer hesitates to draw definite and quantitative conclusions on the basis of the small amount of data available. Nevertheless, one might well expect a distribution similar to the one shown by the inset diagram in Figure 2 (which, incidentally, can be drawn exactly from the present data) on the basis of theoretical considerations alone.

BYERS [see "References" at end of discussion, 1944] refers to CHURCH'S work as follows: "Statements based on earlier observations in the Arctic to the effect that a temperature difference of about 8°C [between air and water] was necessary [for steam fog formation] did not appear to be substantiated." Such conclusion could hardly have been drawn from the data in his Table 1, since the lowest value for $(T_W - T_a)$ is 9°.6 C.

CHURCH includes one observation of steam fog which occurred in Tennessee (over a creek). This observation does not fit any of those obtained over Lake Michigan, but agreement should not be expected. Conditions over a small creek where later mixing (and air drainage) processes are important and probably seriously affect the values for T_a, E_S, and E_a observed at a height of

seven m, could hardly be compared with those obtained over a large body of water where horizontal mixing processes within the boundary layer can undoubtedly be neglected. For true comparisons, the boundary layer within which the observations should be obtained over the small creek is measured in centimeters rather than in meters. According to this line of reasoning, the lake measurements should be more exact for setting up the critical limits for fog formation even though the actual fog forming processes would be identical over both lake and small creek.

Conclusfons

1. Even though no rigorous theoretical solution to the problem of defining the limits for steam fog formation is attempted, it appears that the critical limits which define steam fog of various horizontal densities can be given excellently by the quantity $(E_w - E_s)$, measured at a height of seven m above the water surface, thick to dense fog occurring with $(E_w - E_s)$ equal to or greater than 5.2 mbs and with traces of fog appearing with $(E_w - E_s)$ greater than 4.25 mbs to 4.5 mbs. An indifferent relationship is shown between character and limits of fog and the quantity $(E_w - E_a)$.

2. The vertical extent of the fog appears to be related to the quantity $(T_w - T_a)$, the greater this value the greater the vertical development of the fog.

3. The critical limits for both steam fog formation and the vertical extent of the fog for given temperature and humidity differences between the surface and seven m appear to be independent of the wind speed measured at seven m.

4. The conclusions of previous investigators to the effect that a temperature difference between water and air of approximately 8°C is required before steam fog can form has not been disproved by the data obtained over Lake Michigan.

5. Measurements of temperatures and humidities at levels of the order of seven m over a small creek can not be used to determine the critical temperature and humidity limits for steam fog formation over large water bodies.

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BYERS, HORACE ROBERT, General meteorology, McGraw-Hill, New York, 1944.

PHIL E. CHURCH (University of Washington, Seattle, Wash., Author's closure)--It is encouraging that enough notice has been given the subject of steam fog so that two men have taken the trouble to analyze further the data published in this paper. Their discussions may be a step in the right direction in stimulating further study of critical formation conditions and in solving the problem, but neither of them agrees in toto with my conclusions, nor do they agree with each other, except at certain places.

JACOBS, in using the raw data, concludes that the quantity $(E_w - E_s)$ is the governing factor; as a result he finds that the critical difference of vapor pressure is somewhat less than I gave. This I would not criticize. He chooses, however, to find fault with my statment that ". . . steam fog will not occur, be visible, until the difference $(E_w - E_a)$ is approximately five mbs" by stating that there are 12 of 43 observations recorded cases of fog when the difference is less than five mbs. The term "approximately" was used advisedly. Only two of 43 observations had "traces" with a difference of less than 4.8 mbs; those two might be questionable. He further takes me to task on my statement that "with a vapor pressure difference of more than 5.5 mbs nearly always there were columns that extended upward into the low strato-cumulus cloud deck on the east side of the lake" by stating that the data showed only four of 13 cases in which $(E_w - E_a)$ was greater than 5.5 mbs was fog reported as "columnar." Those cases in which the fog was reported as "columnar," in which the vapor pressure difference was more than 5.5 mbs were on the east side of the lake. A more careful reading of that sentence is suggested. In addition JACOBS states that "only four of the eight cases reported as 'columnar' occurred with $(E_w - E_a)$ less than 5.5 mbs." Three of these four occurred on one cruise from which no wet bulb readings could be obtained and the air was assumed to be saturated. If the air was not saturated those three would undoubtedly have shown a vapor pressure difference of more than 5.5 mbs; the other was with a difference of 5.38 mbs. JACOBS'S attention is called to the fact that the published table for Cruise 16 contained a note stating that there were no readings of wet-bulb temperatures. My statement on page 356 that ". . . this phenomenon is of relatively common occurrence elsewhere at other seasons . . ." follows the body of my paper, in which I pointed out that the critical conditions necessary for the formation of the fog within the temperature range of my data had already been stated. Bearing that in mind, it is

difficult for me to visualize why JACOBS states that "... steam fog would be of almost universal daily occurrence over nearly all oceans during all seasons and over large portions of the continents during the warmer seasons."

JACOBS further criticizes BYERS'S statement [1944, p. 513] that "a temperature difference of about 8°C (between air and water) was necessary (for steam fog formation) did not appear to be substantiated" by stating that "such conclusion could hardly have been drawn in his (CHURCH'S) Table 1 since the lowest value for ($T_W - T_a$) is 9°.6 C." May I bring to JACOBS'S attention that the lowest value in Table 1 in which steam fog, dense too, was presented is 7°.2 C! True it is that such was found over a creek in Tennessee; still the difference is less than 8°C.

The classification table was only a suggested one; JACOBS'S evaluation of it may be accepted, though I feel that any such attempted classification would be doomed to failure at the outset.

The discussion by MILLER contains more meat. While it is true that direct use was not made of the observations to determine the critical condition of formation, the arguments stated are unassailable. However, it can be pointed out that the columns which extend upward into the low strato-cumulus deck on the east side probably do not pierce any inversion; the strato-cumulus deck is a manifestation of the enormous discharge of vapor from the water that occurs as the air travels across the lake. Lastly, I do not see that his paragraph on relative humidity has any noteworthy bearing on the subject.

Lets have more observations on this type of fog wherever observations can be taken over all types of surfaces where the phenomenon occurs.

LETTERS TO EDITOR

MULTIPLE RAIN GAGES

The inscription of "Averages" at the foot of the table in my "Note on Multiple Rain Gages" [Trans. Amer. Geophys. Union, v. 26, pp. 267-68, 1945] is not quite accurate. The figures indicated are the direction and inclination of the resultant vector for all the rains at the particular station, during the period May to October, 1943, and correspond to the figures given in the same columns for individual months. The direction and inclination of the vector resulting from the addition of two, or any number of vectors, are not the "averages" of the directions and inclinations of the separate vectors. The characteristic of the method used is that any rain may be represented by the x, y, and z components of a vector, the catch on any given surface being the same as if the x, y, and z components were intercepted separately, so that the catch on the surface from any number of intermediate rains of undetermined directions and inclinations is mathematically the same as that of a single rain with x, y, and z components, respectively, equal to the sums of those of the separate rains. The components registered by the multiple gage are the vertical component $z = R_v$, the north-south horizontal component $x = r_n - r_s$, and the east-west horizontal component $y = r_e - r_w$. And the "cardinal points" are not those "of the compass," but true north, east, south, and west.

I would have corrected the additions that were made to my manuscript if the delay of many months that habitually occurred in the transmission of correspondence during the War had not prevented the submission to me of a proof of my note before its publication.

H. G. FOURCADE

Witte Els Bosch, C. P., South Africa
January 10, 1946

Transactions, American Geophysical Union Volume 27, Number IV August 1946

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NOTES AND PERSONALIA

NOTES

Vocational booklets--The National Roster of Scientific and Specialized Personnel has issued the first three of its series of Vocational Booklets; these are, respectively, Geology as a Profession, Chemistry as a Profession, and Chemical Engineering as a Profession. Geophysicists will find Booklet no. 1 especially interesting. Booklet no. 4 will relate to meteorology, and will be published soon. Booklet no. 5 will relate to geophysics in general, and will probably be published late in 1946.

Earthquakes in May and June 1946--On May 15 a shock of non-destructive intensity occurred in the northern part of the Gulf Coastal Plain near Doniphan, Missouri at 6:10 U. T. The tremor, described by observers as a severe jar accompanied by a roaring noise, awakened people in Missouri, Kentucky, and Tennessee. Seismograph records were obtained at Cape Girardeau, St. Louis, Florissant, and Cincinnati. The Island of Martinique in the West Indies was rocked by a violent earthquake on May 21. Damage to numerous church steeples and houses was reported by the press. One person was reported killed and three injured in Fort-de-France. A very severe earthquake was felt over a wide Pacific Coast area on June 23. Early reports indicate that the affected area extended from Olympia, Washington to the Pacific Coast of British Columbia and inland as far as Kelowna, B. C. A wall collapsed at Port Alberni; land shifted at Campbell River; rock slides occurred along the railway connecting Port Alberni and Victoria; damage was apparently heavy at Courtenay with waves sweeping in from the sea. Tall buildings swayed in Vancouver, and in Seattle. Mabel Wood reported from Seattle that a chandelier in a hotel lobby suspended 12-15 ft from the ceiling vibrated for some time with a half-amplitude of 16-20 in. The Lions Gate Suspension Bridge at Vancouver swayed considerably. The seismograph records at St. Louis, Missouri, were strong and showed quite a bit of short-period motion. Several stations indicated a difficulty in ascertaining the beginning of the S phase. With the instrumental data of Berkeley, Fordham, Pasadena, St. Louis, State College, Tacubaya, Tucson, and Ukiah available at the Central Station of the JSA, the epicenter was tentatively located in the Strait of Georgia (50°N, 125°W), origin time $17^h13^m15^s$ U. T. This determination will undoubtedly require some adjustment as to location and origin time as soon as more data are received, especially from stations in Alaska. The following provisional epicenters were reported by the United States Coast and Geodetic Survey cooperating with the Jesuit Seismological Association, Science Service, and a selected group of widely-scattered seismological stations.

Date	Time U. T.	Location and remarks
May 3	$22^h23.4^m$	9°S, 153°E, New Guinea
May 8	5 20.3	1°S, 98°E, West of Sumatra
May 9	23 34.4	22°N, 108°W, Gulf of California
May 15	22 10.6	16°N, 96°W, Off Southern Mexico
May 21	9 16.6	14°.2 N, 60°.8 W, Damage on Martinique
June 7	4 13.3	17°N, 94°W, Depth over 100 km

Operation Crossroads--Many members of the American Geophysical Union have been at work at Bikini Atoll in connection with the tests of the atomic bomb. Benjamin Holzman, Colonel in the Air Weather Service, has been the chief meteorologist and Charles C. Bates has been engaged in oceanographic and geologic surveys. Among the others in attendance are W. W. Rubey, Don Kirkham, M. P. O'Brien, and Parker Trask.

New meteorological magazine--A new monthly magazine, Weather, is being published by the Royal Meteorological Society. It includes short articles, comments on current weather, and book reviews, and will be a medium for the lighter type of meteorological material.

The dire straits of Hungarian scientists--A recent communication of A. Réthley, Director of the Hungarian Meteorological Institute, to C. F. Brooks, mention was made of the dire straits in which scientists in Hungary have been reduced during and since the War. He mentions that Budapest is in ruins, and that most of his personal possessions, except his library, were destroyed. His own staff, consisting of 26 scientists and 64 others, are suffering from starvation and lack of suitable clothing and shelter, and are further in need of scientific literature, of which they have been deprived. Their publications are available, but under their reduced circumstances, they have not the funds for postage. Salaries have been reduced to the vanishing point, largely because of inflation. (Dr. Brooks notes that the envelope has 260,000,000 pengos in stamps, whereas before the War, one-half pengo sufficed.) They are unable to purchase vitamin-containing foods, essential to the maintenance of good health. Contributions of food, clothing, and scientific literature should be sent to Dr. A. Réthly, Hungarian Meteorological Institute, Budapest 114, Hungary.

Ice Atlas of the Northern Hemisphere--The Hydrographic Office of the Navy Department has just issued the Ice Atlas of the Northern Hemisphere. It is about 25 inches square and contains more than a hundred pages of charts, tables, and bibliography.

PERSONALIA

Julian D. Barksdale has returned from duty with the Navy in the Pacific area and is again teaching at the University of Washington, Seattle.

Charles C. Bates, who has been on oceanographic and geologic surveys of Bikini Atoll in connection with Operation Crossroads has been appointed Associate Oceanographer in the newly-organized Oceanographic Division of the Hydrographic Office of the Navy Department. He will be stationed in Washington, D. C.

Francis Birch has resumed his teaching duties at Harvard University after having been engaged in research work with the Navy.

John A. Fleming, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington since 1935, retired as Director on June 30, 1946, and has undertaken an assignment on the development of international scientific relations for the Institution. He has been succeeded as Director by Merle A. Tuve, who has been with the Department since 1926, with the exception of the war years, during which he was in charge of the Johns Hopkins Laboratory of Applied Physics, which, among other notable accomplishments, developed the radio proximity fuse.

Ralph E. Gibson of George Washington University, on leave from the Geophysical Laboratory, Carnegie Institution of Washington for special war work, has been given the Special Naval Ordnance Development Award for his work at the Allegheny Ballistics Laboratory.

R. W. Goranson, who has been doing research work with the Navy, has returned to the Geophysical Laboratory, Carnegie Institution of Washington.

J. W. Grieg, who was with the Army Air Forces during the War as a member of one of the operations analysis sections, has returned to the Geophysical Laboratory, Carnegie Institution of Washington.

Fred Keller, Jr. is now on the staff of the Section of Geophysics, United States Geological Survey, and is now working on airborne magnetometer surveys in Alaska. He was formerly on magnetic work with the United States Coast and Geodetic Survey.

Don Kirkham has accepted the position of Associate Professor in the Department of Agronomy and Physics, Iowa State College, to be in charge of soil physics work. During the summer he has been on work at Bikini Atoll, and earlier was with the Naval Ordnance Laboratory.

L. Don Leet of Harvard University was recently elected Corresponding Secretary of the American Academy of Arts and Sciences.

Donald B. MacMillan is now leading a scientific expedition into Arctic waters of Baffin Land aboard his famed exploring schooner, the Bowdoin, in search of ornithological and oceanographic data. The expedition plans to return in August.

David H. Miller, who during the War was in charge of meteorological and terrain observation and analysis programs of quartermaster field trials of clothing and equipment, has resumed work with the Corps of Engineers. He is stationed with the San Francisco Division, working on cooperative snow investigations.

E. Peterschmitt is again preparing preliminary bulletins on earthquake reports at the Institut de Physique du Globe in Strasbourg after four years as a prisoner of war in Germany, during much of which time he worked as an assistant of Dr. Hiller in Stuttgart.

Robert Schinner has continued his research work in Graz, Austria, and has published a number of papers on problems bearing on geophysics and geology.

Hans Stille of Berlin is continuing his study of problems concerning the structure of the Earth.

T. Wayland Vaughan, Associate in Paleontology of the Smithsonian Institution and Director Emeritus of the Scripps Institution of Oceanography, was recently awarded the Mary Clark Thompson Medal by the National Academy of Sciences "in recognition of his outstanding achievement in such purposeful and ingenious coordination of observations and generalizations made in and bearing on the fields of stratigraphic geology and paleontology."

Gilbert F. White has been appointed President of Haverford College, Pennsylvania.

Georges Perrier, for many years General Secretary of the Association of Geodesy of the International Union of Geodesy and Geophysics, died at his home in Paris in February 1946. In the early years of the present century, he was the leader of geodetic expeditions in South America, North Africa, Albania, and Syria. He was a member of the French Academy of Sciences. His work as General Secretary of the Association of Geodesy is being carried on by P. Tardi at his former address, 19 Rue Auber, Paris 9^{e}.

Transactions, American Geophysical Union Volume 27, Number IV August 1946

TWENTY-SEVENTH ANNUAL MEETING (1946)

MINUTES, GENERAL ASSEMBLY AND SECTIONS

EVENING LECTURE SESSION

The Evening Lecture Session of the General Assembly of the American Geophysical Union was held at $20^{h}00^{m}$, May 27, 1946, in Room 1, Hall of Government, George Washington University. The lecture was a presentation by L. C. Graton of a colored motion picture of the Parfcutin Volcano, with an account of the Volcano from its origin to recent days. President L. H. Adams presided at the meeting, and following the formal presentation, Dr. Graton answered questions from the floor.

The picture was a compilation of many films, some by O. O. Fisher, some by W. F. Foshag, many by Dr. Graton, as well as prints of the very earliest film made a few days after the birth of the Volcano. The pictures showed *bocas*, lava flows, and *hornitos*, as well as many views of the main Volcano. Many of the pictures were taken at night and were very colorful.

About 150 members and guests were present, despite very inclement weather.

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was called to order by President L. H. Adams at $13^{h}35^{m}$ on Tuesday, May 28, 1946, in Room 102, Hall of Government of George Washington University, Washington, D. C. The registered attendance at the Twenty-Seventh Annual Meeting was 710 members and guests.

The minutes of the General Assembly of the Twenty-Sixth Annual Meeting on June 1, 1945, were published in the *Transactions* [v. 26, no. 1, pp. 139-160, 1945] and distributed to all members in good standing. They were approved as printed.

The annual report of the General Secretary (see Appendix A) was summarized briefly and accepted with thanks.

Reports of Standing Committees

Statutes and By-Laws--Chairman Harradon reported that the By-Laws as amended a year ago had been approved and were published in the *Transactions* [v. 26, no. 1, pp. 172-177, 1945].

Membership--Chairman Musgrave reported that the growth of the Union has been good and that the membership has cooperated splendidly with the Membership Committee in securing new members, and congratulated both groups on their activity. He announced that over 200 have become new members since January 1, 1946--about 40 per month.

Meetings--Chairman Marble reviewed the situation concerning the Annual Meeting briefly [see Appendix B].

Nominations--Chairman Weightman mentioned briefly that his Committee has been working on the matter of the procedure for elections by mail ballot under the revised Statutes and By-Laws, and that a preliminary report had been presented to the Executive Committee at the meeting on January 14, 1946. A revision of this report was presented subsequently to the Executive Committee following the Business Meeting of the Union [see pp. 610 and 612-613].

Budget--Chairman R. M. Wilson summarized briefly the budget to be laid before the Executive Committee following the Business Meeting [see pp. 611-612].

Editorial and Publication Committee--Chairman Fleming reported that the *Transactions* are currently being published bimonthly in editions of 3500, of which about 3000 are immediately distributed. He stated that the co-Editors representing the several Sections on the Committee have greatly aided editorial work and formulation of policies relating to the *Transactions*.

Reports of Special Committees

Geophysical and Geological Study of Ocean Basins--Chairman Hess communicated a brief report [see Appendix C].

Geophysical and Geological Study of Continents--Chairman Thom reported that during the year 1945-46, the Committee has been chiefly occupied in assembling material for the revised map of the Basement Complex for parts of the United States east of the Great Basin. Various Committee members have been guiding compilations for different regions. It is expected that the complete map can be ready for distribution by June 1947. The Committee has taken part in informal discussions of geophysical-geological projects, which will prospectively be carried forward in continental areas outside of the United States by appropriate organizations within the countries concerned.

Time-Signal Service--Chairman Sollenberger made a brief report concerning the difficulties in standardizing time signals, and the fact that the Naval Observatory has no means of its own for sending out such signals. This was done at one time through the Western Union alone, but now also in cooperation with the National Bureau of Standards. He noted the difficulty of observations of time because of the unfavorable atmospheric conditions in Washington.

Cosmic-Terrestrial Relationships--Chairman Stetson communicated a report which appears as Appendix D.

Award of the William Bowie Medal--Chairman Bucher reported the unanimous recommendation by the Committee that Dr. Reginald Aldworth Daly be awarded the eighth William Bowie Medal.

Surveys and Maps--Chairman Borden reported that, while the Committee had had no formal meetings during the year, it had been active. The two Resolutions, passed last year relating to the better distribution of maps and charts and to the over-classification of maps, charts, and source material, have had beneficial results. Definite progress was made in disseminating information regarding the distribution of such material. The Committee stands ready to assist any interested person or organization in securing information as to place of publication, cost, and so on of any kind of map. The Bureau of the Budget has indicated that the Geological Survey is the official governmental source of information on maps and charts. While less definite progress has been made with regard to the second Resolution, it was noted that, while in the normal change from war to peace there has been a general declassification of maps and charts and a general removal of restrictions, there is little likelihood that Army and Navy chiefs will place the job of classification in the hands of any civilian interdepartmental board.

Affiliation with the American Geological Institute--In the absence of Chairman Thom, Dr. Longwell, who is the representative of the Geological Society of America on the Special Committee of Delegates for the study of this problem, pointed out that at least four of the 13 interested organizations have ratified the constitution of the new Geological Institute. Two committees, appointed by the delegates who had met in October 1945 to study particular phases of the matter, have not yet submitted reports for transmission to the interested societies.

A motion was made and carried that the reports of the various Committees be accepted and referred to the Executive Committee for any necessary action.

Resolutions--Chairman Ingerson recommended the consideration of seven Resolutions which, after discussion, were unanimously adopted as follows:

(1) RESOLUTION OF THANKS TO THE GEORGE WASHINGTON UNIVERSITY

WHEREAS, The 1946 meetings of the American Geophysical Union have been made possible by the kind provision of space and facilities by the George Washington University, and

WHEREAS, The meetings have been aided by the courteous cooperation of the authorities of the University, therefore be it

RESOLVED, That the American Geophysical Union extend its heartiest thanks to the George Washington University for its hospitality and request the General Secretary to express its gratitude to the President of the University.

(2) RESOLUTION OF APPRECIATION TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for these many years extended facilities to the American Geophysical Union in the provision of space for office and storage at the Institution's Department of Terrestrial Magnetism, and

WHEREAS, This courtesy has greatly facilitated the work of the Union, and

WHEREAS, The operating expenses of the Union have been very materially reduced thereby, therefore be it

RESOLVED, That the American Geophysical Union express its grateful appreciation to the Carnegie Institution of Washington for the continuation of these most helpful facilities, and be it further

RESOLVED, That copies of this Resolution be sent to the President of the Carnegie Institution and to the Chairman of its Board of Trustees.

(3) RESOLUTION OF APPRECIATION OF GENERAL GEORGES PERRIER

The American Geophysical Union learns with deep regret of the death of General Georges Perrier, for many years Secretary of the International Association of Geodesy and holder of many positions of honor and trust, stricken in the midst of his efforts to re-establish scientific cooperation among the nations. The Union mourns the death of a notable geodesist, a great organizer of geophysical science at home and abroad, a wise counselor, and a good friend. It extends to the family of General Perrier the assurance of its deep and sincere sympathy.

(4) RESOLUTION ON AVAILABILITY OF CLIMATOLOGICAL DATA

WHEREAS, The climatological data collected by the United States Weather Bureau and other agencies are recognized to have great value for many practical problems such as the design of houses, airfields, highways, and so on, and

WHEREAS, This great value is at present lost to the national economy due to the inadequacy in number of Weather Bureau personnel and to the lack of mechanical equipment suitable for processing large volumes of data, therefore be it

RESOLVED, That it is the earnest desire of the Section of Meteorology of the American Geophysical Union that the Chief of the Weather Bureau do everything in his power to rectify this situation, and that appropriations for this purpose will be forthcoming from the Congress of the United States, and that a copy of this resolution be transmitted to the appropriate Federal Officials.

(5) RESOLUTION ON COLLECTION OF HEMISPHERE-WIDE WEATHER REPORTS

WHEREAS, The collection of hemisphere-wide weather reports at the surface and aloft is an indispensable requisite to meteorological research on the general circulation of the atmosphere and long-range forecasting, and

WHEREAS, The practical application of such researches would be of immense value to the civilian economy, therefore be it

RESOLVED, That it is the earnest desire of the Section of Meteorology of the American Geophysical Union, that the United States Weather Bureau do all it can to re-establish the excellent network of upper-air reports maintained during the War and, if possible, to expand it so as to make possible reliable maps, surface and aloft, over the entire Northern Hemisphere, and that a copy of this resolution be sent to the Chief of the United States Weather Bureau.

(6) RESOLUTION OF CONTINUANCE OF THE ASSOCIATION OF GEODESY IN THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

WHEREAS, It has come to the attention of the American Geophysical Union that there is apparently being promoted, in some places, the idea, discussed and discarded at the Edinburgh General Assembly in 1936, that the Association of Geodesy be separated from the International Union of Geodesy and Geophysics and be succeeded through the re-establishment of the old International Geodetic Association, and

WHEREAS, Such procedure would be contrary to the plan of union of coordinated interest and scientific research in Earth physics, and

WHEREAS, Geodesy is distinctly a geophysical science related to the other seven recognized branches of geophysics, and

WHEREAS, Progress in geodesy under the auspices and generous support of the International Union of Geodesy and Geophysics since 1919 has been of marked quality and has greatly shown the need of close collaboration with other fields of Earth sciences, therefore be it

RESOLVED, That the American Geophysical Union would regard replacement of the Association of Geodesy as now associated in the International Union of Geodesy and Geophysics by an independent International Geodetic Association as detrimental and harmful to the progress not only in geodesy but also in the other branches of geophysics, and be it further

RESOLVED, That the American Geophysical Union record its conviction that further progress in all branches of geophysics is to be attained only by united and common effort so effectively demonstrated in the international aims, achievements, and publications of the International Union of Geodesy and Geophysics since its formation in 1919, and be it further

RESOLVED, That copies of this Resolution be communicated to the President, the General Secretary, and the Executive Secretary of the International Union of Geodesy and Geophysics and to the officers of its Associations.

(7) RESOLUTION ON TIME-SIGNAL SERVICES

WHEREAS, There is a vital need in all astronomical, geodetic, magnetic, and seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communication Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this valuable scientific cooperation, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Director of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

Another resolution relating to the adoption of the metric system, was published in preliminary form in the Transactions [v. 27, no. 2, p. 216]. This resolution was not adopted, but it was approved that a Special Committee on the Metric System representing all Sections be appointed, to report to the next Annual Meeting of the Union.

In addition, one resolution from the Section of Meteorology was read for the information of the Union, and three resolutions were reported to the Executive Committee.

New Business

Membership campaign--General Secretary Fleming emphasized the splendid work done by the Committee on Membership, under the chairmanship of H. F. Johnston and later G. W. Musgrave. President Adams commended the two Chairmen and the Committee for the effective work--so vital to the continued growth and service of the Union. An unanimous vote of thanks was given to the Committee.

International Union of Geodesy and Geophysics--It was carried that the American Geophysical Union is heartily in favor of holding an Extraordinary General Assembly of International General Union of Geodesy and Geophysics at Cambridge, England, July 29 to August 2, 1946, as recommended by the Executive Committee of the International Union at its meeting at Oxford in December 1945.

The Executive Committee of the American Geophysical Union is responsible for recommendation of delegates to the National Research Council and is asked to suggest at least one delegate from the United States to attend at Cambridge.

Citation and Award of the William Bowie Medal--In accordance with the recommendation of the Special Committee on the Award of the William Bowie Medal, Chester R. Longwell made the citation for the Eighth Award of the Medal to Reginald A. Daly, for his services to tectonophysics. Dr. Daly was unable to be present, because of illness in his family, but had been notified of the award. President Adams made the presentation in the absence of the recipient, with the request that the General Secretary forward the medal with an appropriate letter. [The citation and reply subsequently received are printed on pp. 457-458.] Mrs. William Bowie was introduced to the meeting by President Adams and referred feelingly to the honor accorded her late husband in the singularly appropriate designation of Dr. Daly.

Adjournment--The Business Session of the Twenty-Seventh Annual Meeting was declared adjourned at 15^h10^m.

Sessions of Sections--The minutes of the meetings of the Sections of the American Geophysical Union, May 27 to May 29, are given in Appendices E to M.

APPENDIX A--REPORT OF GENERAL SECRETARY OF AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-SEVENTH ANNUAL MEETING, MAY 28, 1946

Membership--During the year from June 1945 the American Geophysical Union has shown a steady growth. The membership of qualified geophysicists on May 23, 1946, is 2727--an increase of 282 since June 1, 1945. Now that the War is over, many of our Members who had been placed, upon their requests, upon the Inactive List, are returning to work in Geophysics and resuming affiliation with the Union. It is expected that the Union's membership will total 3000 or more by the summer of 1946. The annual contribution for membership was increased to $5 beginning January 1, 1946.

Since June 1, 1945, the deaths of 16 Members were reported as follows:

Bruno Ulak (killed in action, date unknown)
Milton H. Schoerpner (killed in France, September 12, 1944)
Rudolph G. Kasel (died June 14, 1945)
Charles F. Devine (died June 20, 1945)
Frederic E. Clements (died July 26, 1945)
Robert H. Goddard (died August 10, 1945)
José A. Elliott (died August 25, 1945)
Homer D. Erwin (died September 10, 1945)
Robert W. Adams (died October 13, 1945)

A. R. Whitson (died November 20, 1945)
Gilbert C. Dobson (died December 29, 1945)
Harry Bateman (died January 21, 1946)
Glen L. Parker (died February 12, 1946)
Robert H. Smith (died March 26, 1946)
Claude W. Sopp (died March 31, 1946)
Robert A. Bartlett (died April 28, 1946)

There are four Corresponding Members as follows: Alfonso Contreras Arias and Pedro C. Sánchez of Mexico; Owen Thomas Jones and Harold Jeffreys of England. There are now three paid life members and, because of retirement after 15 years or more of membership, 13 life members.

Executive Committee Meetings--The Executive Committee held meetings June 1, June 16, 1945, and January 25, 1946--each was unusually well attended, by 29, 26, and 34 members, respectively, of the Committee, while at each meeting a number of members were excused because of previous engagements. The minutes of these meetings were reported in full in the Transactions [v. 26, no. 1, pp. 161-169 and 170-172; v. 27, no. 2, pp. 300-303]. In addition to administrative and financial matters, special attention was given to national and international relations.

Meetings--A Joint Regional Meeting--the Union's 18th Regional Meeting--of the South Pacific Regional Committee of the Section of Hydrology in cooperation with the American Society of Agricultural Engineers and the Western Snow Conference was held at Sacramento, California, February 26-28, 1946.

A Tennessee Valley Group of the Union was authorized but has not yet been formed. Two meetings of the Washington (D. C.) Group of the Section of Hydrology were held.

The Twenty-Seventh Annual Meeting of the Union and its Sections was arranged for May 27-29, 1946. Again the Union has the privilege of the facilities of the Hall of Government of the George Washington University through the courtesy of President Cloyd Heck Marvin. The end of World War II is reflected in a registered attendance of 710--one-half again as many as in the two previous Annual Meetings--and in a scientific program of 135 papers and progress reports. The success of this Meeting is the result of the energy of the Committee on Meetings under Chairman John Putnam Marble.

William Bowie Medal--Upon recommendation of the Special Committee on the Award of the William Bowie Medal the eighth award was made to Reginald Aldworth Daly at the General Assembly May 28, 1946.

Publications--Despite the difficulties and increasing costs from the War, publication of the Transactions of the Union--an ever increasingly valuable agent in forwarding Geophysics--was continued. It was possible to begin the long-planned publication of the Transactions on a bimonthly basis with Volume 26 for 1945; that volume was completed in three issues in an edition of 3500 copies each in August, October, and December, 1945. The first two issues of Volume 27 for 1946 have been distributed, and the issue for June will be off the press about June 25. Printed by the offset method, the individual bimonthly numbers have averaged over 150 pages each. With the appointment of co-editors--one for each of seven Sections and two for the Section of Hydrology--who, with reviewers as referees, take active responsibility for acceptance or rejection of papers and for editing, the past high quality of published papers has been enhanced. In the new format the Transactions are divided into seven departments, namely: (1) Scientific and technical papers; (2) discussion of published papers; (3) progress reports; (4) letters to editor; (5) reviews, abstracts and bibliographies; (6) notes and personalia; (7) Union, Section, and Committee activities.

Other Activities--Chief among new activities of the Union during the year was consideration of education in Geophysics and of opportunities for Geophysics as a profession. These are now especially important subjects, particularly so by reason of the many applications of Geophysics developed during the War and now available for general welfare purposes. In connection with this study, educational institutions throughout the country were circularized for information bearing upon such established courses as might afford training in geophysical fields. In the first edition of "Report on Education and Geophysics" [Trans., v. 26, pp. 463-476] there are listed replies and classification of correspondence received from 119 universities distributed in 41 States, one in Hawaii, one in the District of Columbia, and one in Canada. The data show that courses fundamental to Geophysics are quite generally offered. It is apparent that, while only a few schools now have Departments of Geophysics or of Earth Science, there is large opportunity of integrating established curricula for the award of the degree of Bachelor of Geophysics and that students can readily select suitable courses that will fit them for geophysical work. This compilation, which is being added to, has proved of considerable value in answering requests received from many persons, particularly ex-service men, who are interested in the growing opportunities of Geophysics as a life work. In this same connection we have supplied the National Roster of the War Manpower Commission with the necessary particulars for monographs on the profession of Geophysics.

Statutes and By-Laws--Effective July 31, 1945, revised Statutes and By-Laws were adopted by almost unanimous vote of the membership and with approval of the National Research Council. The revision was made to facilitate the Union's broader program of activity with emphasis of democracy of organization. Most notable among the changes are those providing for ballot by mail for elections of officers of the Union and Sections, the designation of more elective members for the Executive Committee of the Union, and provisions for corporation memberships, for regional and local branches or groups, and the appointment of an Executive Secretary.

Finances--As requested by the General Assembly, a statement of receipts and disbursements for the year ending June 30, 1946 will be submitted for audit in July. Since the summer of 1944, the Union has received payments regularly under a total grant of $20,000 for three years from the Rockefeller Foundation. This generous assistance has eased the manifold administrative difficulties occasioned by the War and has enabled the Union better to fulfill its obligations to Geophysics and mankind than could otherwise have been possible.

The National Research Council, as in past years, made an allotment of $400 to the Union for the fiscal year ending June 30, 1946.

Under the terms of Robert E. Horton's will, the Union will receive, through the National Research Council, 70 per cent of the residual estate upon the death of his widow, and other stipulated life interests in the estate; this bequest may eventually amount to $150,000 or more. The Union has already received Dr. Horton's "notes and filed pamphlets" and is to receive $5,000 for the completion of certain manuscript material relating to Hydrology.

Committees--The Committees of the American Geophysical Union have continued study in their respective fields, particularly the Committee on Geophysical and Geological Study of Ocean Basins, the Committee on Geophysical and Geological Study of Continents, and the Committee on Cosmic-Terrestrial Relations. The Committee on Surveys and Maps has made substantial progress in integrating war-time efforts for postwar use.

International relations--As heretofore, the Union and its Officers have maintained relations to insure rehabilitation of the International Scientific Unions. Meetings of the Executive Committees of the International Council of Scientific Unions (ICSU) were held in London during December 4-5, 1945, and of the International Union of Geodesy and Geophysics (IUGG) in Oxford during December 10-14, 1945. The first was attended by J. A. Fleming and W. D. Lambert as Members of ICSU with R. M. Field as a guest. The meeting of IUGG was represented for the National Research Council and the American Geophysical Union by Messrs. Field, Lambert, and Fleming. It was decided at these meetings that, as the first step in the rehabilitation of the International Unions following the War, there should be a General Assembly of ICSU in London during June 1946, an Extraordinary General Assembly of IUGG at Cambridge, England, during July 29 to August 2, 1946, and the Eighth General Assembly of IUGG in Norway during the summer of 1947. The last was called for 1942 in Norway but could not be held because of the War. A Special Committee was appointed by ICSU to discuss with a similar committee of the proposed United Nations Educational, Scientific, and Cultural Organization (UNESCO) the future relations between the Council and its individual Unions and UNESCO; it was emphasized that the arrangements ultimately made should be such as to maintain the autonomy of ICSU and of the individual Unions. Accounts of these meetings have been published in the Transactions [v. 27, pp. 145-148, 209-214] and in the Journal of Terrestrial Magnetism and Atmospheric Electricity [v. 51, pp. 31-35, 103-118, and 119-121].

An example of the growing tendency toward applications of Geophysics is the inauguration by the Executive Committee of IUGG of a Committee on the Social Value of the Earth's Sciences whose objective is to prepare a general statement on the value of the Earth's sciences for human welfare and to institute such other forms of publicity that from time to time may be desirable. This Committee consists of representatives from Great Britain, Canada, Denmark, France, Italy, Mexico, Norway, Sweden, Switzerland, and the United States.

Payment of dues for adherance of the United States to IUGG for the calendar years ($3,920.40 per year) 1944 and 1945 has been promised by the Department of State sometime in July 1946. The balance now deposited in Riggs National Bank at Washington, D. C., is $14,943.82, after deducting travel expenses, as authorized by General Secretary Winterbotham, for trip of Messrs. Field and Lambert to England and return in December 1945; expenses for J. A. Fleming were provided by the Carnegie Institution of Washington.

Conclusion--Developments during the War in Geophysics, bearing, for example, on radio-communication disturbances, radar, isomagnetic maps, improved instruments for aerial surveys, development of water resources, control of erosion, and many other subjects point to their great future peace-time value and aid in solving many complex problems. It is of interest to note that the number of Members of other Nations of the Western Hemisphere adhering to the Union has considerably increased during the year. The distribution of the Transactions among geophysicists in all parts of the world, which can now be resumed, is an important factor in forwarding international collaboration. These are examples only that indicate continuing progress in Geophysics, embracing the whole Earth, which will contribute much to the advancement of human welfare and to international good-will.

JNO. A. FLEMING, General Secretary
American Geophysical Union

APPENDIX B--REPORT OF THE COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

Merrill Bernard
G. B. Cressey
C. L. Garner
R. A. Hertzler
W. D. Sutcliffe

The Committee on Meetings is faced with a difficult problem in finding space suitable for the Annual Meetings of the American Geophysical Union, at a time and place convenient to a majority of the membership. As the number attending the Annual Meeting will continually increase with the growth in the rolls of the Union membership, this problem will grow more pressing in future years.

The present arrangements, whereby the Union are the guests of the George Washington University is convenient, inasmuch as we can meet in Sections under one roof, with no cost for rooms or service (except for projection facilities); but we have to hold the meetings at a time when the rooms are not being used for teaching purposes. This limits us as to dates quite strictly, and in the last few years has made it impossible to combine our Annual Meeting with the Washington spring meetings of other scientific bodies.

Other space, such as a selection of the various Government auditoria, may be arranged for at perhaps a more convenient time, but not more than three Sections could be accomodated under one roof, unless the total time of the Meeting were to be spread out over four or five days.

There is nowhere outside of Washington a great concentration of our membership in any one city, so that it appears essential that our Annual Meeting continue to be held there. The possibility of holding an Extraordinary General Meeting as the need may arise, in some other scientific center, is receiving the consideration of your Committee. This would be in addition to the usual Regional and Group Meetings.

Your Committee is already committed to holding a special evening lecture or symposium in Washington at the time of the Winter Meeting of the Executive Committee of the Union, and would appreciate suggestions as to topics and speakers.

APPENDIX C--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEAN BASINS

H. H. Hess, Chairman

Maurice Ewing
C. S. Piggot
Paul A. Smith
Harlan T. Stetson
Thomas G. Thompson

With the termination of the War, the Committee has resumed its activities relating to investigation of ocean basins. The following projects are under way or in an active planning status:

(1) The Hydrographic Office, United States Navy, will print in the near future a detailed bathymetric chart of the Western Pacific covering the area from Japan to Northern New Guinea and including the Marianas, Western Carolines, and Philippines. This project was made possible by the tens of thousands of soundings obtained by United States Naval vessels during war-time cruising.

(2) The areas from New Guinea to New Zealand and from the Marianas to the Hawaiian Islands have also been contoured and presumably will form the bases for two more bathymetric charts. The discovery of 160 flat-topped peaks between the Hawaiian Islands and the Marianas offers an intriguing problem for research at sea.

(3) Maurice Ewing reports that the Vening Meinesz pendulum apparatus has been obtained from Sir Hubert Wilkins and will be turned over to the custody of the Woods Hole Oceanographic Institution. Plans are now in progress to continue gravity-at-sea investigations in the Caribbean and on the west coasts of Colombia, Equador, and Peru, starting in the spring of 1947, with earlier shorter cruises along the Atlantic Continental Shelf.

(4) W. W. Atwood of the Army Map Service has been contacted with the view toward having constructed a solid model of a portion of the bathymetric chart mentioned under (1). It has been reported to the Chairman that Major Atwood was much interested in the project and would make an experimental model in the near future.

(5) The Hydrographer, United States Navy, has taken steps to encourage United States Naval vessels and ships of the Merchant Marine to take and send in to the Hydrographic Office more soundings in the deep sea. Stress has been laid on accuracy in observing the depths and locating their geographic positions. Undoubtedly a great wealth of new data will result from this policy. It seems likely that the greatest advances in the understanding of the geology and structure of ocean basins which may be expected in the next decade will result from the study of ocean bottom topography.

Projects of first-order importance on which it is hoped work will be started or resumed in the near future are as follows:

(1) Seismic work at sea--Continuation of work on profiles across the Continental Shelf of eastern North America. It is hoped that these can be extended outward to the foot of the continental slope, since such a traverse would shed much light on the unsolved problem of the origin of the slope and would complete the structural picture of the shelf. The Chairman understands that Maurice Ewing and his colleagues are interested in continuing the seismic work interrupted by the War.

(2) Seismic work at sea--Determination should be made of total thickness of sediments on the floor of the deep sea preferably far from shore in the Central Pacific Basin. Equipment to do seismic work in very deep water has not yet been constructed. It is hoped that this project will be undertaken since information of very fundamental character could be so obtained.

(3) Magnetic investigations at sea--Airborne magnetic instruments promise to develop a whole new field for research in geomagnetism since vast areas can be covered in a relatively short time. No specific projects are suggested in this field but as rapid regional reconnaissance surveys are made it can be expected that these will serve as a guide to specific problems. The magnetic investigation of atolls should now become a relatively simple problem.

(4) Bottom sampling--C. S. Piggot is still on active duty in the Navy. It is hoped that his important bottom-sampling work will be resumed on his return to a civilian status.

(5) Atolls--The Chairman strongly recommends that a project be started to investigate thoroughly by geophysical methods and drilling one of the typical atolls of the Pacific Basin. This is a problem which has intrigued scientists for over a hundred years since Charles Darwin's observations during the voyage of the *Beagle*. In spite of the scholarly work of Dana, Davis, Daly, Gardiner, Vaughan, David, Bonney, Sollas, Judd, Ladd, Hoffmeister, Stearns, and a host of others, there still remain a myriad of opinions and a dearth of facts as to what underlies the atolls. If but a fraction of the energy consumed in heated argumentation on this problem during the past century could be put into the useful purpose of direct observation and measurement today, the problem could easily and finally be resolved.

The Chairman has endeavored to keep in contact with various government agencies and scientific organizations, as well as individual scientists, interested in, or related to, those scientific investigations at sea which come within the fields of activity of the Committee. At present there seems to be greater interest in work at sea than at any time in the past.

APPENDIX D--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR 1945-1946

Harlan T. Stetson, Chairman

C. F. Brooks	N. H. Heck	H. Landsberg
H. H. Clayton	J. F. Hellweg	J. Q. Stewart
J. H. Dellinger	E. O. Hulburt	W. T. Thom, Jr.
J. A. Fleming		N. Wiener

The members of this Committee have been active during the past year not only in their respective investigations but in an endeavor to coordinate interrelated material in the general subject matter which is the concern of your Committee. It is particularly fortunate that with the termination of the War, there is again opportunity for the interchange of material that heretofore has had to come under the classification of "restricted." The rapid rise in solar activity during the year has given abundant opportunity for the study of geomagnetic and ionospheric correlations. Members of the Committee have been helpful in supplying and analyzing much data in cooperation with the Interservice Radio Propagation Laboratory of the National Bureau of Standards, other Government agencies, the Carnegie Institution of Washington, Harvard Observatory, and other private organizations. The request for predictions of the next sunspot maximum resulted in individual determinations by three members on the Committee who have given 1948.0, 1948.2, and 1948.3. The agreement by the different methods appears good and would seem to foretell the peak of solar activity to occur in the early part of 1948.

An all-day conference was held under the auspices of the Committee at the laboratory in Needham, Massachusetts, on December 11, 1945, for a general discussion of cosmic correlations, particularly as concerns ionospheric and tropospheric effects in the propagation of radio waves of both medium and very high frequencies. The purpose of the meeting was to bring together experts from universities, communication companies, radio industries, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the National Bureau of Standards, and the Federal Communications Commission for an informal discussion of cosmic effects influencing radio wave propagation. Participating in the discussions were E. H. Armstrong, H. H. Beverage, C. F. Brooks, C. W. Carnahan, P. A. deMars, H. B. Marvin, F. A. Vening Meinesz, H. R. Mimno, G. W. Pickard, V. Regener, H. T. Stetson, J. A. Stratton, O. G. Villard, H. W. Wells, G. Worsley, and others. The group was fortunate in having present as an honored guest F. A. Vening Meinesz, whose presence was timely on account of representing the interests of Government of the Netherlands in the future development of the sciences in that country.

Cosmic factors and the ionization of the atmosphere, from sunspots to meteors, introduced the morning session. The importance of the relationship between critical frequencies and the sunspot curve is well recognized in predicting wave-lengths in world-wide communications. The importance of field-intensity measurements made over a long period of time as a test of performance and a check on the success of predictions was made evident from exhibits presented.

Attention was given to the desirability for additional stations throughout the world capable of broadcasting continuously well-controlled, standard-frequency signals such as are emitted from the National Bureau of Standards station at Beltsville, Maryland. Continuous field-intensity records of such signals around the World would provide needed supplementary information to ionospheric soundings now being made. It was also suggested that a coordinated program of absorption measurements at ionospheric stations should be made as soon as facilities become available.

The afternoon session was devoted to a discussion of VHF transmission from 30 Mc up. Stetson and Pickard exhibited the results of field-intensity measurements of W2XMN, Alpine, New Jersey (42.8 Mc), as received during the year at Needham. These showed a marked seasonal variation with the maximum field recorded in September, 1945. Pickard called attention to the fact that this was consistent with measurements taken by himself at Seabrook Beach for WGTR (44.3 Mc) in 1941. It has been suggested that sporadic-E ionization may be of some importance in FM reception beyond the line of sight. Pickard showed, however, that a study of sporadic-E ionization occurrences showed no significant correlation with the Alpine reception at Needham over the 150-mile path.

A comparison of Alpine's reception of upper atmospheric data, provided by F. W. Reichelderfer of the Weather Bureau, has shown important relations to temperature gradients and water-vapor content. It appears probable that the chief atmospheric effects involved occur well below the 5000-foot level.

The subject of tropospheric transmission has been an important one because of the ever increasing demand for transmission and reception at higher frequencies. Differences of opinion as to the relative merits of the higher-frequency bands can possibly best be settled through the study of performance by means of field-intensity records that are now rapidly accumulating for the VHF region of the radio spectrum.

A more recent report on the relation of tropospheric transmission to refraction and water-vapor content was presented by two of our members at the joint meeting of the International Union of Scientific Radio (ISRU) of the Institute of Radio Engineers (IRE) in Washington, May 2 and 3, 1946. The Committee has plans for adding materially to the field-intensity-recording program in cooperation with the newly-organized Central Radio Propagation Laboratory (CRPL) in Washington and through further investigation of other items in the field of Cosmic-Terrestrial Relationships.

Charles F. Brooks (Blue Hill Observatory of Harvard University, Milton, Massachusetts)--During the past year we have continued our record of total radiation on a horizontal surface with the Eppley pyrheliometer and micromax recorder; also, of the radiation at normal incidence with the Eppley tube and micromax recorder, the same as in prévious years since 1932. From time to time the Schott filters red and yellow RG_2 and OG_1 have been used to divide the spectrum.

The automatic records obtained with these instruments have been evaluated for the most part by the United States Weather Bureau Solar Radiation Supervising Headquarters here at Blue Hill, and daily totals of total radiation and intensities at different unit air-masses for the radiation at normal incidence have been published in the Monthly Weather Review.

In addition to the instruments belonging to the Blue Hill Observatory the United States Weather Bureau, in the early half of last year, installed three additional Eppley pyrheliometers, one to measure the total radiation on a vertical east-facing surface, one a vertical south-facing surface, and the third, the diffuse radiation from the sky alone. This latter instrument is shaded from the Sun by a ring of iron pipe two inches in diameter 20 inches from the instrument. The position of this pipe is adjusted from week to week.

A slight improvement in exposure of the pyrheliometer was made this spring by the construction of an iron shelf extending six feet out from the south wall of the top of the tower, thereby getting farther away from the superstructure of the mast carrying anemometers and wind vane.

Several investigations have been in progress at the Observatory in the past year. The project of total solar and sky radiation in relation to cloudiness and cloud-density that was started in 1944 by Bernhard Haurwitz was completed and published in the Journal of Meteorology [v. 2, no. 3, pp. 154-166, 1945].

An attempt was made to find a way to combine into a unit figure the effects of cloudiness and cloud density on the amount of radiation from the Sun received on a horizontal surface, but Haurwitz reports that the two variables do not seem to be amenable to such a combination in any reasonably simple manner. Haurwitz is beginning a study of the albedo of clouds of different densities hoping to divide the total loss between absorption in the cloud and reflection from the cloud.

A computation of the intensity of the diffuse radiation from the sky has been under way. From the total radiation on a horizontal surface is subtracted the horizontal component of the direct radiation from the Sun at normal incidence. Only a few months have yet been computed, but it is intended to compare these computed values with the recorded ones and with generalized computations made by W. Gorczynski a year ago on the basis of the ratio of diffuse to total radiation at different altitudes of the Sun and different degrees of cloudiness at Nice (France) and Gdynia (Poland).

The Weather Bureau has been analyzing currently the data received on the vertical surfaces, and a paper on solar energy received on a vertical surface facing south was presented by Irving Hand at the Annual Meeting in Washington in May 1946. Some comparisons have been made between the Weather Bureau pyrheliometers on the Federal Building in Boston and ours here at Blue Hill. Further details of the Weather Bureau's work in pyrheliometry, which is quite comprehensive in that it involves tabulations and study of the records from all stations in the United States, may be had from the Weather Bureau itself.

Another study which has been in progress during the year is further comparisons of the indications of instruments which record only the duration of bright sunshine with those indicating the intensities of the solar radiation. The two duration instruments compared are the Campbell-

Stokes burning-glass type of sunshine recorder and the United States Weather Bureau thermoelectric sunshine-radiation recorder. The former records only when the direct solar beam is strong enough to burn a hole in a card when focussed. The latter, however, will record when the combination of the direct beam and insolation from the sky is sufficient to raise the temperature of the solar thermometer to a certain amount above the air temperature. The study is not yet ready for publication.

Another field of research in cosmic-terrestrial relations involves the variability of solar emission and its effect upon the weather. This has been in continuation of work which H. H. Clayton has been carrying on for many years. Haurwitz has made a preliminary study of the physical possibility of a solar flare so increasing the temperature of the ozone layer to a greater degree in the tropics than at high latitudes that a redistribution of pressure at high levels sufficient in size to have observable effects on the pressure and, consequently, on the weather at the Earth's surface can take place. The results of his preliminary survey have been published in the Transactions of of the American Geophysical Union [v. 27, no. 2, pp. 161-163, 1946].

At Mr. Clayton's request, and with funds supplied by John A. Robling, I. I. Schell is making a statistical test of the relation between large two-day increases in relative sunspot numbers and the incidence of anti-cyclones in the northern interior of North America during the cold season, November to March, inclusive.

H. T. Stetson--Clayton has pursued further the possibilities of planetary effects as a significant factor in the cause of solar activity. Taking into account the times of maximum heliographic latitudes of the planets in turn, he has been able to produce with surprising accuracy the sunspot curve for the last hundred years. An examination of his graphs places the next maximum of the current sunspot cycle at 1948, in agreement with the predictions previously quoted.

Your Committee greatfully acknowledges the solar and geophysical data supplied through the courtesy of J. F. Hellweg, Superintendent of the Naval Observatory, and his successor, R. S. Wentworth, and John A. Fleming, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Acknowledgment is also due to John H. Dellinger, Chief of the Interservice Radio Propagation Laboratory (now the Central Radio Propagation Laboratory) for promptly supplying ionospheric data from many cooperating stations which has facilitated the study of the interrelationships of cosmic phenomena which has been the concern of your Committee.

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting was called to order by the President, W. D. Sutcliffe, at 09^h10^m, May 28, 1946, in Room 202, Hall of Government, George Washington University, Washington, D. C.

The minutes of the previous meeting having been published and no corrections or additions received, the President declared them approved as published.

J. B. Small, representative of the Section of Geodesy on the Committee on Membership of the Union reported that the Committee had been very active during the past year. Several meetings had been held with Chairman Musgrave of the Committee, to discuss ways and means of informing prospective Members about the work of the Union. It was recommended that Members, who come into contact daily with non-members of the Union who are engaged in the field of Geophysics inform them of the work of the Union and invite them to apply for membership. Small asked any present and interested in becoming Members to see him after the meeting.

C. A. Whitten, member of the Editorial and Publication Committee representing the Section, reported on the progress of the Transactions during the past year. Members of the Section were urged to submit discussions of the papers which had been published as well as for the papers to be presented at the Meeting. Members were also invited to contribute news items, book reviews, bibliography, or criticisms. He stated that the Committee appreciated the assistance and suggestions made by the members during the past year.

C. J. Clifford, Chairman of the Resolutions Committee proposed a resolution mourning the death of General Georges Perrier, for many years Secretary of the International Association of Geodesy. This resolution was approved for submission to the Union [see Minutes of Business Meeting, Resolution 3]. W. D. Lambert gave a brief account of the career of General Perrier.

R. M. Wilson, Chairman of the Committee on Nominations, reported that no nominations were to be made at this time, and that the Committee offered to cooperate with the general Committee on Nominations of the Union in reaching an agreement on the method of making nominations and of elections by mail ballot.

The Business Meeting of the Section was adjourned, and the following scientific papers were presented:

(1) W. D. Lambert: Deflections of the vertical from gravity anomalies
Discussion by Fletcher Watson, C. H. Swick, and H. C. Mitchell
(2) Noel Ogilvie: Astronomical control for war-time mapping in northern Canada (read by H. S. Rappleye)
(3) F. R. Gossett and A. D. Sollins: Experimental azimuth determination from non-circumpolar stars near elongation; experimental position determination by pendulum astrolabe (read by A. D. Sollins)
Discussion by W. D. Lambert and H. W. Hemple
(4) C. I. Aslakson and D. A. Rice: Use of shoran in geodetic control (read by D. A. Rice)
Discussion by Sigmund Hammer, C. C. Wang, O. S. Reading, John A. O'Keefe, Fletcher G. Watson, and C. L. Garner
(5) F. W. Hough: Readjustment of central European triangulation (by title)
(6) John A. O'Keefe: Approximate datum adjustments
(7) Sigmund Hammer: Gravimeter tie between gravity base stations in Washington, D. C., and its relation to international gravity comparison
Discussion by L. B. Tuckerman
(8) H. W. Hemple: Recent progress in geodetic surveys of the United States Coast and Geodetic Survey
(9) Manuel Medina: Geodetic work in Mexico during the period from May 1945 to March 1946 (by title)

Several visitors from South America and China were introduced.

The meeting adjourned at $11^{h}47^{m}$.

FRANK L. CULLEY, Acting Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting of the Section of Seismology was called to order by the President, V. C. Stechschulte, at $14^{h}00^{m}$, May 27, 1946, in the Hall of Government, George Washington University, Washington, D. C.

The Secretary noted that the papers by James B. Macelwane (Report of the Jesuit Seismological Association), William C. Repetti (Seventy-five years of seismology at the Manila Observatory), and Albert J. Frank [Earthquake of March 27, 1945 on the Moselle (Missouri) Fault] were omitted from the previous minutes. The paper by Goberna and Buckie should not have been listed, since it was withdrawn previous to the Meeting. Aside from these changes the reading of the minutes was dispensed with, and they were declared approved as published in the Transactions [v. 26, pp. 153-154, 1945].

The Section's Committee on Resolutions (Frank Neumann, Chairman) asked that the Chairman of the Committee on Resolutions for the Union be contacted in order to include the Section in the general resolution on Accurate Time Service adopted by the Union. This action was unanimously adopted and referred to the Committee on Resolutions of the Union.

The Chairman of the Special Committee on Nominations to consider methods for handling future elections in the Section (R. R. Bodle, Chairman, J. B. Macelwane, and H. H. Neuberger) read the report which follows: Since voting is to be done by mail in accordance with the Statutes of the Union, this Committee on Nominations recommends that: (a) Nominations are to be by mail ballot; (b) the Executive Committee shall constitute a Committee on Nominations and Elections; (c) the Committee on Nominations and Elections shall declare nominated all those who have appreciable votes and place their names on the ballot; (d) the process of nominations should be completed by January 1 preceding the election.

It was unanimously adopted that this report be presented to the Executive Committee of the Union. If this report conflicts with any regulations on mail ballots set up by the Executive Committee of the Union, the Executive Committee of the Section is empowered with the authority to make any necessary revisions.

There being no further business, the Section proceeded to the scientific papers as follows:

(1) Elliott B. Roberts: Progress report on the seismological work of the United States Coast and Geodetic Survey for 1945-46 (by title)
(2) Harold W. Murray: Submarine relief of the Aleutian Trench
(3) L. Don Leet: Velocity of P in the granitic layer (read by L. M. Murphy)
(4) Ralph R. Bodle: A note on the earthquake and seismic sea wave of April 1, 1946
(5) Beno Gutenberg: Earthquake study in southern California (read by J. B. Macelwane)
(6) V. Conrad: Annual frequency variations of earthquakes and geological structure (read by L. M. Murphy)
(7) Marion H. Gilmore: Microseisms classified according to type of storm (read by Frank Neumann)
(8) Fred Keller, Sr.: Response characteristics of electronic earthquake recorder
(9) Leonard M. Murphy: Microseisms, the unknown
(10) Anatol J. Schneiderov: On some atomic age possibilities in seismology and tectonophysics

The meeting adjourned at $16^{h}10^{m}$.

LEONARD M. MURPHY, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting of the Section of Meteorology was held May 27 and 28, 1946, in three sessions, in Room 101, Hall of Government, George Washington University. About 250 Members and guests were present.

The opening session, President F. W. Reichelderfer presiding, was held $09^{h}15^{m}$ to $12^{h}00^{m}$, May 27, 1946. The reading of the minutes of the previous meeting was dispensed with, as they had already been printed in the Transactions [v. 26, no. 1, pp. 154-155, 1945], and no corrections or additions had been received.

President Reichelderfer drew attention to the Committee on Resolutions (H. Wexler, Chairman, R. K. Linsley, and R. G. Stone) and pointed out that any resolutions proposed must be in the hands of the Committee in time for submission to the Section at the close of the afternoon session, May 27. He stated that there would be no report this year from the Research Committee on Climatology, as the Chairman and members had been so occupied with other urgent matters that no time had been found for work of the Committee. He expressed confidence that considerable would be reported next year.

The President mentioned the titles of two papers which had been received too late for inclusion in the printed program but which could be submitted for inclusion in the Transactions. They were: Meteorological program at the tent-exposure test, Camp Lee, Virginia, and analyses of observations of summer, 1945, by David H. Miller; and Atmospheric pressure cycles at Batavia and their association with terrestrial-magnetic activity, by H. B. Maris.

The afternoon session of May 27, held from $14^{h}10^{m}$ to $17^{h}00^{m}$, was a joint meeting with the American Meteorological Society. Accordingly, during the first half of the session, H. R. Byers, Vice-President of the Section of Meteorology, and thereafter, H. G. Houghton, President of the American Meteorological Society, presided. At the close of the session, three resolutions submitted by Chairman Wexler were approved.

The morning session of May 28 was held from $09^{h}15^{m}$ to $11^{h}30^{m}$ also jointly with the American Meteorological Society, the presiding officers being H. R. Byers for the Section and H. Wexler for the Society. It consisted of a symposium on tropical cyclones at which five papers were presented.

The scientific program for the three sessions consisted of the following papers:

(1) J. Namias: Report of the Research Committee on Extended Forecasts

(2) B. G. Holzman and Robert C. Bundgaard: The analysis of horizontal divergence in the atmosphere (presented by Robert C. Bundgaard)
(3) J. B. Kincer: Our changing climate
(4) R. E. Falconer: Use of Pitot tube to compensate for pressure deficiency due to wind on Mount Washington
(5) V. Conrad: Some remarks about formulas of continentality (by title)
(6) Ronald L. Ives: Automatic range switching equipment for the Grinnell wind-speed recorder
(7) Ronald L. Ives: An interpolating contactor for 16-point recording from a standard 8-point wind vane
(8) Phil E. Church and C. A. Gosline, Jr.: Characteristics of mixing and the dilution of waste stack gases in the atmosphere
(9) C. F. Brooks: Ratios between maximum wind velocities for different short intervals of time
(10) C. F. Brooks: Estimates of maximum ice accumulations and rime on exposed objects at different altitudes and latitudes in the United States
(11) Harry Wexler and H. N. Norton: Analysis of pressure and temperature data observed during the flight of the Explorer II
(12) François Matthes: The present state of knowledge concerning atmospheric movements over Greenland
(13) S. S. Visher: Regional contrasts in heat-day units in the United States (presented by Earl Thom)
(14) C. G. P. Beer and Luna B. Leopold: Meteorological factors influencing atmospheric pollution in the Los Angeles Basin
(15) Bernhard Haurwitz: Motion of pairs of tropical cyclones
(16) R. D. Fletcher: Seasonal weather analysis of southeast Asia (by title)
(17) R. S. Simpson: Forecasting movement of tropical cyclones
(18) S. B. Solot: Haboobs in the Anglo-Egyptian Sudan
(19) Leo Alpert: Atmospheric cross-sections over the tropical eastern Pacific Ocean
(20) L. P. Harrison: Dynamic theory of pressure deficiency produced on mountain tops

H. D. HARRADON, Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting of the Section of Terrestrial Magnetism and Electricity was held in the Hall of Government, George Washington University, on May 28, 1946. The session was called to order at 09^h12^m in Room 203, with Vice-President Irwin Roman occupying the chair in the absence of President Johnston. There were approximately 70 members and guests in attendance.

It was moved and seconded that the minutes of the Twenty-Sixth Annual Meeting, together with the addendum thereto containing discussions of papers, be accepted in the form in which they were published [Trans., v. 26, no. 1, pp. 155-156, 1945, and v. 27, no. 2, pp. 304-305, 1946]. This motion was carried without discussion.

The Committee on Units was called upon for a report. Its Chairman, H. H. Howe, stated that because of inactivity of the Committee during the year, it had no official report, but that an informal report detailing the history of the Committee and outlining proposed action on three propositions had recently been submitted by him [Trans., v. 27, no. 2, pp. 215-217, 1946]. He also pointed out that in consequence of action taken at the 1944 meeting, it would now seem appropriate to ascertain the will of the Section as to the problems of nomenclature already discussed. He offered a motion to approve the resolution contained in Proposition A of his informal report, dealing with the names of certain units of resistivity. This motion was seconded, and the ensuing discussion centered on the portion having to do with volume resistivity. Howe pointed out that the oft-used expressions "ohms per cubic centimeter" and "ohms per cubic meter" were erroneous, since by the definition of resistivity its dimensions must be given by

$$\rho = RA/L = [R]\,[L]$$

where R is resistance, A is cross-sectional area, and L is length. He reminded the Section that a recommendation for action in this matter had been formally approved by the Committee in 1943. A. G. McNish expressed opposition to the resolution, stating his opinion that no harm came from the use of the names claimed to be faulty, since there was no likelihood of confusion or misunderstanding of the actual intended meaning. Others participated in the discussion, pointing out that the fault seemed to center in the use of the word "per" which had not originally been part of the names, the concept being properly that of the resistance between two opposite faces of a unit cube. When put to a vote by show of hands, the motion elicited five favorable votes and four opposed. The Chair held that the meager interest in the subject seemed to preclude a clear expression of opinion, and that the resolution was neither approved nor rejected, but was open for consideration at a future meeting.

McNish then made a motion that the Committee on Units be dissolved in view of its admitted inactivity. He averred that it was a waste of time to give repeated consideration to such matters. The motion was seconded and passed by a vote of 8 to 4, and the thanks of the Section were tendered to the members of the Committee for their efforts to deal with a difficult situation.

There was an announcement to the effect that a Committee on Nominations was to be appointed at about the beginning of 1947 and that Members should submit their suggestions as to the composition of this Committee at that time or sooner.

Under the head of new business, Dr. Howe offered a motion that the Section approve and transmit to the Union the resolution embodied in Proposition C of his report, recommending wider use of the metric system (pp. 216-217). This motion was seconded and passed by a vote of 13 to 7.

The scientific program proceeded at 09^h30^m with the following papers and discussions thereof:

(1) Victor F. Hess: On the ionization produced by the gamma rays from Quincy granite
(2) Frank A. Benedetto: Simultaneous cosmic-ray measurements on the Empire State Tower and at Fordham University
(3) M. L. Phillips: Variations in sporadic-E ionization observed at Washington, D. C.
(4) A. G. McNish: Outline for future research in geomagnetism
(5) E. H. Vestine, L. Laporte, and C. Cooper: Geomagnetic secular change at various epochs
(6) D. S. Hughes and W. L. Pondrom: Computation of vertical magnetic anomalies from total magnetic field (read in abstract, neither author being present)
(7) Fred Keller, Jr. and Albert J. Hanners: A continuously recording declination station
(8) H. B. Maris: Probability analysis of geomagnetic activity
(9) A. H. Shapley: The variation of the recurrence tendency in magnetic activity with the solar cycle
(10) Elliott B. Roberts: Current magnetic work of the United States Coast and Geodetic Survey (by title)
(11) J. A. Fleming: Researches in terrestrial magnetism and electricity at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, from April 1945 through March 1946 (by title)

The paper presented by Mrs. Phillips elicited some discussion, which was opened by S. E. Forbush. He referred to the influence on magnetic character-figures of the equinoctial effect. H. W. Wells pointed out that the analysis of Watheroo sporadic-E ionization fails to confirm the findings of this paper, but seems to indicate a trend that is 180° out of phase. He thought it would probably be premature to draw any conclusions as to the origin of abnormal-E ionization, that there seems to be a discrepancy between the Northern and Southern Hemispheres such that predictions for one would not hold for the other. He noted also that recordings made at College (Alaska) during the War would indicate close relation there between sporadic E and overhead aurora, though there is not overhead aurora every time there is sporadic E, and that there is a very definite distribution of frequency of occurrence of sporadic E with latitude. At stations near the magnetic equator, such as Huancayo, the manifestation of sporadic E in its intense form with multiple reflection is very rarely observed, though there is a fringe type that is not rare.

In reply, the author noted that the Watheroo data were open to criticism because of variations in the power of emission, referring to Interservice Radio Propagation Laboratory report R-34. The same applied to College and Huancayo; also, the observations were on the second multiple reflection, which involves absorption to twice as great as an extent as does the first-multiple reflection, since the signals are affected twice by the atmosphere. She stated that the data used in her paper are all based on the first multiple, and that the ratio of the second multiple to the first vanishes in midday (especially at the equinoxes), citing IRPL R-36 in this connection. Since the absorption bears a direct relation to the sporadic E itself, the results using the second multiple are more ambiguous than those using the first. Further, the variation with geomagnetic latitude is very pronounced, with night values very low around the equator; the delay time for Huancayo is such that low heights cannot be recorded there.

In connection with Mrs. Phillips's paper, C. W. Gartlein mentioned the pre-dawn dip in auroral activity. L. V. Berkner pointed out that sporadic-E ionization is not a very clear concept, and that it involves several possible definitions; fundamentally what is meant by sporadic E is nothing more than the occurrence of echoes beyond normal ones. The author stated that in her usage the blanketing type was not included, but only clouds or patches of abnormal ionization.

There was no discussion of any of the other papers on the program, and the meeting was adjourned at 12^h10^m.

DAVID G. KNAPP, Secretary

APPENDIX I--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting of the Section of Oceanography was held in Room 202, Hall of Government, George Washington University, on May 27, 1946. The meeting was called to order by Vice-President Schmitt at 09^h10^m. About 130 members and guests were present.

The minutes of the previous meeting were approved as published in the Transactions [v. 26, pp. 156-157, 1945].

As there was no business to transact the meeting proceeded to the scientific session under which the following papers were presented:

(1) R. O. Glover: Recent developments in oceanography at the Hydrographic Office
(1A) L. H. Rumbaugh: Further requirements for oceanographic research for Naval Ordnance applications
(2) J. F. Farley: Oceanographic work of the United States Coast Guard in 1945 and plans for 1946 (read by G. Van A. Graves)
(3) L. O. Colbert: Oceanographic activities of the United States Coast and Geodetic Survey
(4) H. U. Sverdrup: Research within physical oceanography and submarine geology at the Scripps Institution of Oceanography during April 1945 and April 1946
(5) Phil E. Church: Postwar plans of the Oceanographic Laboratories of the University of Washington
(6) C. K. Green: The seismic sea wave of April 1, 1946 as recorded by tide gages
(7) H. U. Sverdrup and W. H. Munk: Theoretical and empirical relations between wind, sea, and swell (by title)
(8) H. A. Marmer: The use of mean sea level as a geophysical datum
(9) C. J. Fish: Oceanography in Japan
(10) John C. Armstrong: The oceanography of Kii Suido
(11) H. R. Seiwell: Military oceanography in tactical operations of World War II

President Sverdrup, who had been delayed by the railroad strike, arrived at 11^h40^m. After giving a résumé of his paper he spoke on the important part played by oceanography during the War and the bright prospects for the future.

The meeting adjourned at 12^h18^m.

L. P. DISNEY, Secretary

APPENDIX J--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Seventh Annual Meeting of the Section of Volcanology was called to order by President R. E. Fuller May 27, 1946, at 14^h10^m in Room 203, Hall of Government, George Washington University, Washington, D. C.

There was no business to transact and no reports from Committees.

Seven scientific papers were then presented as follows:

(1) P. W. Guild: Petrology and structure of the Moa, Cuba, Chromite District
(2) R. H. Jahns: Origin of mica-bearing pegmatites in the southeastern and southwestern United States (presented by W. R. Griffitts)
(3) G. D. Robinson: Volcano investigation in Alaska by the United States Geological Survey (presented by J. C. Reed)

(4) D. E. White and others: Preliminary results of studies of quicksilver and antimony deposits at Steamboat Springs, Washoe County, Nevada (presented by T. P. Thayer)
(5) W. F. Foshag and E. P. Henderson: Primary sublimates of Parícutin Volcano (presented by J. P. Marble)
(6) Fred Keller, Jr.: The magnetic work of the United States Coast and Geodetic Survey at Parícutin Volcano, Michoacan, Mexico (presented by Ralph Bodle)
(7) R. E. Fuller: Developments at Parícutin during the past year (based on observations of Howell Williams, Konrad Krauskopf, and the author)

Papers (1), (4), (6), and (7) were accompanied by lantern slides, many of those of (7) being color photos of the Volcano and its environs.

The meeting adjourned at $17^{h}05^{m}$.

PHILIP W. GUILD, Acting Secretary

APPENDIX K--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

On Sunday, May 26, 1946, a group of 19 Members and friends were guests of the Pennsylvania Water and Power Company for an inspection of the hydro-electric plant on the Susquehanna River at Safe Harbor, Pennsylvania, arranged by Carroll F. Merriam. After a substantial and delicious lunch at the community house of the Company, the party was conducted through the plant. Details of construction and operation of the dam, gates, control room, turbines, and generators were shown and explained by Carroll F. Merriam, Office of Special Studies, Paul M. Hess, Station Superintendent, and E. T. Schuleen, Test Department.

All regular sessions of the Section were held in Room 102 of the Hall of Government of George Washington University, Washington, D. C., on May 27, 28, and 29, 1946. The Business Meeting was called to order by President Church at $09^{h}15^{m}$, May 27, 1946. Minutes of the 1945 meeting were approved as published in the Transactions [v. 26, no. 1, pp. 158-159, 1945].

The Secretary announced the following actions of the Executive Committee:

(a) The following Chairmen of Committees have been appointed: L. A. Richards to succeed F. J. Veihmeyer, Research Committee on Physics of Soil Moisture; R. G. Farrow to succeed J. E. Church, Research Committee on Snow; Phil E. Church to succeed S. T. Harding, Research Committee on Lakes; and W. W. Horner, Committee on Inter-Society Relations.

(b) The Subcommittee on Permeability of the Research Committee on Ground Water, on recommendation of S. W. Lohman, was made a Special Research Committee on Permeability with C. E. Jacob as Chairman, to continue until its objectives have been reached.

For the Committee on Honors and Awards, the Secretary announced that there were no eligible papers during 1945 for consideration as the best first paper by a young hydrologist, and that no award was made for a paper making an outstanding contribution to hydrology [for Report of the Committee, see Appendix L].

A report on the formation and the activities of the Washington Group of the Section of Hydrology was presented by C. F. Izzard, Vice-Chairman of the Group.

President Church briefly reviewed progress for the past year. The Business Meeting adjourned at $09^{h}40^{m}$ and immediately the first scientific session was begun. The President introduced Past President Meinzer, who took the chair for this session, at which the following reports and papers were presented:

(R1) W. C. Lowdermilk: Report of the Research Committee on Erosion
  (1) W. D. Ellison: Rain-drops and soil-erosion, a motion-picture in color with sound
  (2) W. C. Lowdermilk and R. W. Bailey: Certain effects of volcanic ash of Parícutin on hydrology of the area (with motion-pictures)
  (3) Merrill Bernard: Hydrology in the Soviet Union
  (4) W. J. Roberts and H. E. Romine: Effect of train-loading on the water-level in a deep glacial-drift well in central Illinois (presented by Max Suter)
(R2) S. W. Lohman: Report of the Research Committee on Ground Water
(R2a) C. E. Jacob: Report of the Subcommittee on Permeability

The session adjourned at $11^{h}35^{m}$.

The second session was called to order at $14^{h}02^{m}$ on May 27, 1946, by S. W. Lohman, and the following papers, constituting a Symposium on Ground Water, were presented:

(5) O. E. Meinzer: Suggestions as to future research in groundwater hydrology
(6) W. L. Broadhurst, W. O. George, and R. W. Sundstrom: Accuracy of pumping-test method and non-equilibrium formula for computing future draw-down in wells (presented by W. M. White)
(7) B. A. Barnes and Penn Livingston: Value of the electric log for estimating groundwater supplies and the quality of the ground water (presented by W. M. White)
(8) W. O. Smith: The specific yield of uniform sands
(9) R. G. Kazmann: Increasing groundwater supplies through the induced infiltration of surface water
(10) C. E. Jacob: Boundary conditions in groundwater hydraulics
(11) C. C. Williams and S. W. Lohman: Method of estimating groundwater supplies in the Wichita, Kansas, well-field area
(12) C. K. Wentworth: Progress in the estimating of groundwater supplies in Hawaii (presented by A. N. Sayre)
(13) Max Suter: Apparent changes in water-storage during floods at Peoria, Illinois
(14) N. A. Rose: A check of actual and computed draw-downs in wells in the Lufkin area, Texas
(15) N. A. Rose: Relation of phenomenal rise of water-levels to a defective gas-well, Harris County, Texas

The session adjourned at $17^{h}06^{m}$.

The third session was called to order at $09^{h}15^{m}$ on May 28, 1946, by R. S. Goodridge, and the following reports and papers were presented:

(R3) G. W. Musgrave: Report of the Research Committee on Infiltration
(16) L. L. Harrold: The time relationships, lysimeter-infiltration and percolation compared to watershed-runoff (presented by W. D. Potter)
(R4) R. W. Davenport: Report of the Research Committee on Runoff
(17) E. G. Dunford and P. W. Fletcher: Effect of the removal of streambank vegetation upon water-yield
(18) J. A. Lieberman and P. W. Fletcher: Further studies of the balanced water-cycle on experimental watersheds
(19) C. O. Clark: A basis for unified flood-control operation of reservoir-systems
(R5) L. G. Straub: Report of the Research Committee on Dynamics of Streams (by title)
(R5a) E. W. Lane: Report of the Subcommittee on Sediment Terminology (by title)
(20) I. L. Steinberg: Flood-routing (by title)
(21) H. J. Putman: The backwater curve
(22) Gerard H. Matthes: Macro-turbulence in natural stream-flow
Discussion by François E. Matthes
(23) L. C. Gottschalk: A method of estimating sediment-accumulation in stock-ponds
(24) E. W. Lane: Grade-changes in Cherry Creek, Denver, Colorado (by title)

The session adjourned at $12^{h}30^{m}$.

The fourth session was called to order at $09^{h}10^{m}$ on May 29, 1946, by G. W. Musgrave, and the following reports and papers were presented:

(R6) Merrill Bernard: Report of the Research Committee on Precipitation
(25) W. C. Spreen: Graphical correlation for determining the effect of topography on precipitation
(26) R. K. Linsley, Jr.: Frequency and seasonal distribution of precipitation over large areas
(R7) F. J. Veihmeyer: Report of the Research Committee on Physics of Soil Moisture (by title)
(R8) H. G. Wilm: Report of the Research Committee on Evaporation and Transpiration (by title)
(27) E. A. Colman: The place of electric soil-moisture meters in hydrologic research (by title)
(28) H. W. Anderson: The effect of freezing on soil-moisture and on evaporation from a bare soil (by title)
(R9) C. S. Howard: Report on the Research Committee on Chemistry of Natural Waters (by title)
(R10) S. T. Harding: Report of the Research Committee on Lakes (by title) (Phil E. Church, newly appointed Chairman, reported briefly on plans for next year)
(29) Phil E. Church: Some ice-forms in Lake Michigan
(30) R. P. Sharp: Suitability of ice for aircraft-landings (presented by François E. Matthes)
(R11) Francois E. Matthes: Report of the Research Committee on Glaciers

(31) V. J. Schaefer: Properties of single particles of snow and the effects they produce in storms
(R12) J. E. Church: Report of the Research Committee on Snow

The following resolution, proposed by R. S. Goodridge, was adopted unanimously:

RESOLUTION OF THANKS TO THE PENNSYLVANIA WATER AND POWER COMPANY

WHEREAS, Nineteen members of the American Geophysical Union, Section of Hydrology, availed themselves of the opportunity to inspect the hydroelectric plant of the Safe Harbor Water Power Corporation on the Susquehanna River on May 26, 1946, and were refreshed and benefited by the guided tour, and

WHEREAS, Such inspections, conducted by men of the Company distinguished by alertness, courtesy, and a comprehensive knowledge of all matters pertinent thereto and of interest to the members attending, broaden understanding of applied hydrology and afford opportunity to discuss informally views and interpretations of relevant theory, therefore be it

RESOLVED, By the Section of Hydrology assembled in Washington, D. C., May 27, 1946, that the Section extend its heartiest thanks to the Pennsylvania Water and Power Company for its hospitality and request the Secretary to express its gratitude to the President of the Company, Mr. John A. Walls, and be it further

RESOLVED, That the appreciation of the Section of Hydrology be expressed by the Secretary to President Walls for the many courtesies extended to its members through Carroll F. Merriam, Paul M. Hess, and E. T. Schuleen.

The session adjourned at 12^h15^m

K. HILDING BEIJ, Secretary

APPENDIX L--REPORT OF COMMITTEE ON HONORS AND AWARDS OF THE SECTION OF HYDROLOGY, MAY 27, 1946

No authors of papers on hydrology published in the Transactions during the calendar year 1945 were eligible for the award for the best first paper published by a young hydrologist. No choice of a paper making an outstanding contribution to scientific hydrology was made by the Committee, and therefore no award is made this year.

In order that the aims of the Committee on Honors and Awards, and its procedure in attaining them, be made generally known, the Secretary has been instructed to prepare the following statement.

The Committee on Honors and Awards was established by the Executive Committee of the Section of Hydrology to stimulate research in hydrology, to encourage younger men who are engaged in hydrologic work to do independent and original thinking, and to secure for the Transactions of the American Geophysical Union the best possible papers that contribute directly to the advancement of hydrologic science, by awards for especially meritorious papers. Two annual awards are established:

(1) An award for the best first paper upon presentation to the American Geophysical Union by a scientist who shall have received his baccalaureate degree within not to exceed 10 years prior to submission of the paper or report (or an equivalent time for an author without degree, as determined by the Committee).

(2) An award for that paper which makes an outstanding contribution to the advancement of scientific hydrology, this award to be open to any author of a paper presented for publication by the American Geophysical Union.

Present rules of the Committee relating to selection of papers for awards are:

(1) The Committee on Honors and Awards of the Section of Hydrology consists of: (a) The members of the Executive Committee, the Chairmen of Research Committees, the Section Editors, and Past Presidents of the Section, serving as the Selection Committee. [The duties of these members are to study papers and to make recommendations to members under (b).] (b) The members of the Executive Committee, serving as the Committee of Award. [The duties of these members are to consider recommendations submitted by the members under (a), to make final selections, and to make the awards.]

(2) Awards shall not be made if papers of sufficient quality have not been published.

(3) Awards shall be based on papers published in the Transactions of the American Geophysical Union during the calendar year preceding the Annual Meeting at which the awards are made [see also (4)].

(4) If only one or a very few papers are eligible for consideration as the "best first paper" in any one year, the Committee may, in view of outstanding quality, make the award; or the Committee may hold these papers for consideration in combination with the papers of the next following year.

(5) Awards for the "best first paper" shall be made to joint authors only when both or all of the authors qualify, and if they so qualify, the award shall be made to all of the joint authors of the "best first paper."

It is, of course, neither to be expected nor to be desired, that papers will be written merely in competition for an award. However, it is hoped that the possibility of an award may lead authors to devote the little extra care and study which will lift papers from the "very good" to the "exceptionally meritorious."

K. HILDING BEIJ, Secretary

APPENDIX M--MINUTES OF THE ANNUAL MEETING OF 1946, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held on the morning of May 27, 1946, in Room 203, Hall of Government, George Washington University, Washington, D. C. The meeting was called to order by President Cloos at 09^h12^m. The minutes of the previous Annual Meeting were approved as published.

As there was no other business to bring before the house, the meeting proceeded with the presentation of the prepared scientific program, which consisted of the following technical papers:

(1) T. P. Thayer and P. W. Guild: Thrust faults and related structures in northeastern Cuba
(2) H. Landsberg: Note on the frequency distribution of geothermal gradients
(3) John Straczek: Tectonic history of south-central Oriente Province, Cuba
(4) L. L. Nettleton and T. A. Elkins: Geologic models made from granular materials
(5) Robert E. Wallace: A portion of the San Andreas Rift in Southern California
(6) Lawrence A. Warner: Structural control of ore deposition at Kasaan Peninsula, southeastern Alaska
(7) P. B. King: Activities in tectonics of the Research Committee of the American Association of Petroleum Geologists
(8) H. H. Hess: Drowned and ancient islands of the Pacific Basin
(9) M. King Hubbert: Boundary stresses in mountain deformation

There was liberal discussion of the several papers presented.

The meeting adjourned at 12^h45^m.

On Tuesday, May 28, at 09^h00^m in Room 1 of the Hall of Government, the Section of Tectonophysics participated in a conference on Geophysical and Geological Education, under the chairmanship of Professor Chester R. Longwell. This was the third of a series of such conferences, which are now being administered under the direction of a Committee of the National Research Council. The following formal papers were presented:

(1) Maurice Ewing: Training for research in geophysical borderlands of geology
(2) Edward B. Burwell, Jr.: Engineering geology, and proper training for it
(3) M. H. Trytten: Accrediting as a means of improving undergraduate training in science

Following these papers, there was liberal and extensive discussion of various aspects of this problem, and there seemed to be a gratifying convergence of opinion towards the proposition that in the future, the training in Earth Science must employ considerably more instruction in the fundamental subjects of mathematics, physics, and chemistry, than heretofore has been customary.

A stenotypic record was taken of the proceedings of this conference, and it is to be printed sometime within the next few months by the Geological Society of America as Part 5, Interim Proceedings of the Geological Society of America for 1946.

This conference was adjourned at about 12^h30^m.

M. KING HUBBERT, Secretary

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of May 28, 1946

The meeting was called to order at 15^h20^m in Room 202 of the Hall of Government, George Washington University, Washington, D. C., President L. H. Adams presiding.

Present--Thirty-three persons were present, namely: L. H. Adams, K. H. Beij, W. H. Bucher, J. E. Church, E. Cloos, F. L. Culley, L. P. Disney, J. A. Fleming, R. E. Fuller, H. D. Harradon, M. K. Hubbert, Earl Ingerson, David G. Knapp, W. D. Lambert, W. C. Lowdermilk, R. J. Manly, J. P. Marble, H. E. McComb, A. G. McNish, W. H. Munk, L. M. Murphy, G. W. Musgrave, L. L. Nettleton, I. Roman, W. W. Rubey, Waldo L. Schmitt, Waldo E. Smith, V. C. Stechschulte, W. D. Sutcliffe, H. U. Sverdrup, C. H. Swick, R. H. Weightman, and R. M. Wilson. R. M. Field was excused because of a previous engagement.

Approval of Minutes--The minutes of the meeting of January 25, 1946, were published in the April issue of the Transactions [v. 27, no. 2, pp. 300-303, 1946]. No corrections were received, and they were approved as published.

General Secretary's Report

Personnel--Hazel A. Bower and Marie H. Kolquist of the staff of the American Geophysical Union resigned as of February 15, 1946. Eleanor M. Lanigan, part-time electromatic operator, resigned as of March 31, 1946, and was replaced by Marion Geoffroy for full-time from February 25; Constance G. Coblenz was appointed secretary-stenographer on March 11, 1946.

Financial report--The cash balance on May 1, 1946, in all funds of the Union was $14,943.36. A detailed statement for the year ending June 30, 1946, will be prepared in July and submitted promptly to the Committee on Audit. On May 1 bills receivable for dues for 1945 totalled $4,660.67, and bills payable $999.24; thus assets of the Union were $18,604.79.

The budget for the fiscal year 1946 has been adequate in its total. Certain additional adjustments were made by transfers as follows: To Transactions $1800 to make a total of $7400 (occasioned by increase in the cost of Transactions); to postage and communications $50 to make a total of $900; to Section expenses $25 to make a total of $125.

Payments totalling $7000 for second year of grant from the Rockefeller Foundation have been received.

No payment has been received under the Robert E. Horton will; it is expected that shortly after a Surrogate Court hearing set for July 1, 1946, $5000 for specific purposes defined in the Will will be made available. Thirty-five hundred pounds of notes and filed pamphlets of Dr. Horton have been received and await disposition.

Membership--From January 25 to May 23, 1946, 142 new members have been added to the rolls of the Union, and six who were inactive have been transferred to the active list. There are about 40 additional proposals now in the hands of the Committee on Membership.

Six have been added to the list of life members, after 15 years or more of membership, because of retirement: Frank Adams, Walter S. Adams, A. K. Ludy, Hugh C. Mitchell, Henry F. Moore, and George F. Winchester.

Funds received through paid life memberships now total $300; handling of these funds has been referred to the Committee on Budget as per action of the Executive Committee on January 25, 1946.

Eight deaths have been recorded since January 25 as follows: Charles F. Devine (June 20, 1945), José A. Elliott (August 25, 1945), A. R. Whitson (November 20, 1945), Harry Bateman

(January 21, 1946), Glen L. Parker (February 12, 1946), Robert H. Smith (March 26, 1946), Claude W. Sopp (March 31, 1946), and Robert A. Bartlett (April 28, 1946).

Since January 18, 1946, 15 names have been transferred from the active to the inactive list, and thirty-two members have resigned.

As of May 1, 1946, 686 members were in arrears for dues for 1946, but by May 23, 197 of these had remitted in full in response to a second billing. Fifty-nine members were in arrears on May 1 for 1945 and 1946; by May 23 four of these had remitted in full.

Sixty-seven members were in arrears for two years or more, on January 25, 1946; since then 16 have paid, resigned, or died. Changes of membership from June 1, 1945 to May 23, 1946 are as follows:

Membership as of June 1, 1945	2445	
New members	401	
Inactive to active	11	
		2857
Deaths reported	16	
Active to inactive	23	
Resigned	40	
Dropped for arrearage in dues	51	
		130
Total May 23, 1946		2727

This figure includes: Life members (because of retirement), 13; Life members (paid), 3; Corresponding members, 4; and Members and associates, 2707.

Occasionally a newly-elected member does not qualify because of non-payment of dues. It was approved that the General Secretary be given authority to drop any newly-elected members who do not respond or make payment of dues within six months after election.

National Research Council--The National Research Council has made a grant of $400 to the Union for the fiscal year ending June 30, 1947.

Publications--Since January 25, 1946, the Transactions of February and April, 1946, have been issued and distributed to the membership and subscribers; the June issue is in the hands of the printer. Comments so far received indicate general approval of the modified format used in the April issue. There are about 150 copies of each issue which are on paid subscription account; it is believed that subscriptions may be increased considerably from various technical and scientific libraries as the result of further efforts.

International Union of Geodesy and Geophysics--It is planned to hold an Extraordinary General Assembly of the International Union of Geodesy and Geophysics at Cambridge, England, during July 29 to August 2, 1946. The American Geophysical Union is to send one or two delegates, and W. D. Lambert was endorsed as the delegate from the United States. H. U. Sverdrup and J. Bjerknes, who are to be in Europe this summer, were also endorsed if arrangements can be made and facilities are available at the meeting. All three were recommended for appointment by the National Research Council.

Meetings--The South Pacific Regional Committee of the Section of Hydrology held a regional meeting in cooperation with the American Society of Agricultural Engineers and the Western Snow Conference at Sacramento, California, February 26-28, 1946. The session of February 27 was the one especially allocated to the American Geophysical Union. F. J. Viehmeyer, Chairman of the Regional Committee, reported splendid attendance (104 registered on February 27) and great and sustained interest with lively discussion. Thirty papers were presented during the three-day session--nine on February 27. The meeting of the North Pacific Regional Committee of the Section of Hydrology planned for the late spring has been indefinitely postponed.

The Washington Group of the Section of Hydrology held its second meeting in the YWCA in Washington, D. C., on February 18, 1946. D. B. Krimgold was elected Chairman, Carl F. Izzard, Vice-Chairman, and Bernard Frank, Secretary. Merrill Bernard gave an absorbing account of his visits to the Soviet Union and his inspection of their hydrologic facilities.

National Roster--Word has recently come from W. T. Read of the National Roster that the Roster's plans for publication of the various vocational monographs have been postponed and delayed because of lack of funds; four of these monographs--chemistry, chemical engineering, geology, and meteorology--are now substantially complete, and are to be released before July 1, 1946. The one on geophysics is fifth in the list, and publication is contemplated shortly after July 1.

American Standards Association--The cooperation of the American Geophysical Union with Committee Z-38 on Photography, of the American Standards Association has continued; Commander Mattison is the Union's representative.

Miscellaneous--In accordance with the action of the Executive Committee on January 25, 1946, the recent correspondence relating to the loan of the gravity meter from the Humble Oil Company has been referred to the Committee on Geophysical and Geological Study of Continents (W. T. Thom, Jr., Chairman).

Action on General Secretary's Report--Matters requiring action were acted upon as reported above, and the report was accepted.

Reports of Standing Committees

Budget--Chairman R. M. Wilson read the report of the Committee on Budget, presenting the budget proposed for the year ending June 30, 1947. This was discussed and approved in the form presented in Appendix 1.

Nominations--Chairman Weightman distributed a questionnaire that the Committee had prepared relative to nomination procedures, number of nominees for each office, and related matters, to secure a concensus of opinion with regard to these matters. After explanation of the questionnaires, there was general discussion of the problems, and the questionnaires were filled in by those present for the guidance of the Committee. It was agreed that after the Committee had opportunity to review material turned in, a revised questionnaire with explanatory material would be published in the Transactions to secure comments and opinion from the entire membership, following which the Committee will prepare a further report for action by the Executive Committee to formulate plans for the election of officers for the triennium beginning July 1, 1947. The questionnaire is presented in Appendix 2. Comment and suggestions should reach the office of the Union by September 15 to be considered by the Committee.

Editorial and Publication--Chairman Fleming reported on the activities of the Committee, noting that Ross R. Heinrich has been appointed to the Committee to take the place of Frank Neumann, who resigned. He noted also the more recent resignation of J. B. Kincer. (His successor, subsequently named, is J. R. Fulks.)

Special Committees

Resolutions--Chairman Ingerson reported that 12 resolutions were submitted to the Committee, seven of which were passed by the Business Meeting of the Union, one was referred to a newly-formed Special Committee on Adoption of the Metric System, one was reported as adopted by the Section of Meteorology, not requiring action of the Union, and three, not adopted by any section, were reported on unfavorably and were read to the Executive Committee. The action of the Committee was approved.

Section Matters

Hydrology--President Church reported changes in the inter-society representatives. The following were approved: American Meteorological Society, Charles F. Brooks; American Society of Agricultural Engineers, C. E. Ramser (East) and F. J. Veihmeyer (West); American Society of Civil Engineers, Wesley W. Horner; American Waterworks Association, Samual B. Morris; Geological Society of America, Henry R. Aldrich; Section of Hydrology, W. G. Hoyt; Society of American Foresters, H. G. Wilm; Society of Economic Geologists, Stanley W. Lohman; and Soil Science Society of America, O. R. Neal.

New Business

The General Secretary stated that requests were received from newspapers, broadcasting companies, and scientific publications for copies of, or information concerning, papers to be presented at meetings. When information has been available, it has been supplied subject to the following conditions: Reference may be made to the meeting and the general nature of papers (or a paper) to be presented, but detailed information contained in the paper is not to be published prior to presentation at the meeting. After presentation, abstracts or a popularized version may be published, giving appropriate credit to the author and his organization, and to the Union, but papers will not be published in full or in major part without specific approval of the Union and the author. It was approved that the General Secretary, with the assistance of the Executive Secretary, be authorized to make available material that will be useful in publicizing the work of the Union

The meeting adjourned at 17^h17^m.

JNO. A. FLEMING, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX 1--BUDGET FOR FISCAL YEAR ENDING JUNE 30, 1947

R. M. Wilson, Chairman
R. W. Goranson H. N. Eaton

The following budget for fiscal year 1946-47 was approved by the Executive Committee.

Assets:		
Balance in bank, June 30, 1946, estimated	$12,000	
Bills receivable, including some of the dues in arrears[a]	2,500	$14,500
Grants:		
National Research Council	$ 400	
Rockefeller Foundation[b]	7,000	$ 7,400
Anticipated Income:		
Dues 2800 (net[c]) members for 1947	$14,000	
Sales, Transactions and reprints	4,000	$18,000
Total estimated receipts and assets		$39,900
Suggested Expenditures:		
Transactions, three numbers v. 27 and three numbers v. 28 (900± pages), including services of I. B. M. operator	$ 7,000	
Reprints	2,000	
List of members and officers	750	
Bibliography of Hydrology, 1941-1946 (if manuscript prepared by Section of Hydrology	600	
Services Executive Secretary	6,000	
Stenographic and clerical services	5,400	
Expenses, 28th Annual Meeting	500	
Expenses, Regional Meetings	100	
Expenses of Sections	100	
Expenses of Committees	500	
Honoraria to co-editors	1,500	
Postage and communication	1,000	
Stationery and miscellaneous	1,000	
Bowie Medal	20	
Travel	300	
Office Equipment	600	
Bills payable other than those estimated in arriving at balance in bank June 30, 1946	130	
Total suggested expenditures		$27,500
Estimated balance June 30, 1947		$12,400[d]

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[a] This item assumes that a certain part of unpaid past dues will not be paid because of resignations, overseas duty, transfers to inactive list, and dropping of any becoming two years in arrears.

[b] This is the balance of the Rockefeller Foundation Grant of $20,000 which was made for the three-year period ending June 30, 1947.

[c] The rate of increase in membership during the early months of 1946 indicates that our rolls will well exceed 3000 in 1947, but estimate of income from dues is made conservatively on 2800 members, the approximate membership in May 1946.

[d] It is to be noted that this balance must apply against expenditures during July to December 31, 1947, that is, before dues of 1948 become available.

The Budget Committee wishes to call specific attention to the discrepancy between the anticipated continuing income (estimated as a possible minimum of $18,000) and the proposed expenditures of $27,500. This Committee feels that a vigorous campaign should be inaugurated for increasing receipts so that a more equitable balance may be obtained between receipts and expenditures.

The Committee suggests that the funds received for life memberships be invested in long-term bonds, so that the interest from them will become available at regular intervals in lieu of the annual dues that would otherwise be paid by life members. This procedure protects their interests and at the same time adds to the permanent assets and financial stability of the Union.

It has been proposed that the General Secretary be under bond. This Committee suggests that bond should be provided in order to be consistent with usual businesslike procedure.

APPENDIX 2--REPORT OF STANDING COMMITTEE ON NOMINATIONS, INCLUDING QUESTIONNAIRE ON NOMINATIONS AND ELECTION PROCEDURES

The Committee on Nominations, appointed following the revision of the Statutes and By-Laws in July, 1945, was charged with the responsibility of recommending procedures for carrying out elections of Union officers by mail ballot, as provided by the revised Statutes and By-Laws. It is expected that the Sections will set up procedures for nominations and elections that will permit integration into a single ballot.

On January 25, 1946, a tentative report of the Committee was presented to the Executive Committee. A number of comments were received regarding the plan submitted. On the basis of these and further study by the Committee on Nominations, the matter was again presented to the Executive Committee at its meeting, May 28, 1946 (see page 610). Accordingly, the questionnaire on the next page is submitted in order to secure the opinion of the membership as to the most suitable plan to follow. Each member is asked, therefore, to detach the ballot on the back fly-leaf, mark an (x) in the appropriate box to express his preference, and mail it to the General Secretary by September 15, 1946.

Some comments on the pros and cons are given as follows:

Number of nominees--The Statutes provide for mail ballot for election of officers of the Union as a whole and for its Sections. To many, it seems idle to submit the name of only one nominee for ballot. Occasionally, of course, there would be two nominees because of a possible additional nomination by petition. With regard to having more than one nominee for each office, many nominees would not desire to compete with others and might be averse to taking part in a popularity contest. On the other hand, having only one nominee tends to guide or channel the vote and would provide no opportunity for expressing a choice. Having only one nominee avoids electioneering, and embarrassment to defeated candidates and makes it easier to obtain consent of the most suitable nominee by reason of absence of competition with other candidates.

Nomination by entire membership or by a Committee--In rows (a) to (g) are listed seven methods of nomination which have been suggested as possibilities. Rows (a), (b), and (c) provide for preliminary nominations by the entire membership, and row (f) furnishes a slight variation. Rows (d), (e), and (g) provide for nomination by a committee or committees. It seems evident that, if a committee and not the general membership makes the nominations, that committee should be as representative as possible and reasonably large. The Executive Committee consists of 44 members and can reasonably be considered a representative body. Under (g) various suggestions have been made as to the size of the committee, such as 9, 11, 19, and 24, as well as the method of appointment. It would appear that each Section should be represented on such a committee as well as the Union as a whole.

Nominations made (1)	Election by mail ballot as required by Statutes[a]			
	Only one nominee (2)	More than one nominee (3)	More than two nominees (4)	Number of nominees not specified (5)
(a) By entire membership (nominee or nominees receiving the largest number of votes)				
(b) Through suggestions made by entire membership, and then submitted to Executive Committee for final nomination with privilege of adding other names, due regard being given to Section affiliation				
(c) Through suggestions made by entire membership to a small committee with privilege of adding other names, and finally to Executive Committee with privilege of adding other names				
(d) By a small committee initially (not submitted to entire membership) and then submitted to Executive Committee for final nomination with privilege of adding other names, and of adding names submitted by petition when signed by one per cent of total membership				
(e) By Executive Committee (not submitted to entire membership) but with opportunity of adding names submitted by petition when signed by one per cent of total membership				
(f) Preliminary slate of names prepared by Executive Committee when submitted by preference ballot to entire membership, on basis of which results, Executive Committee elects				
(g) By special Committee appointed by Executive Committee with opportunity of adding names submitted by petition when signed by one per cent of total membership				

[a] See Transactions, v. 26, pp. 172-177, August 1945 for Statutes and By-Laws as revised to July 31, 1945

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SUPPLEMENTARY INFORMATION RELATING TO EDUCATION IN GEOPHYSICS

Since the publication in December [Trans. Amer. Geophys. Union, v. 26, pp. 463-476, 1945] of the tabulated material relating to courses in Geophysics offered by various colleges and universities, additional questionnaires have been received from educational institutions not therein listed, and a correction has been received relative to the data concerning courses at Columbia University.

Table 1--Educational institutions, listed according to States

Key to symbols:

a--Aeronautics	e--Astronomy	h--Chemistry	l--Geography
b--Agriculture	f--Biology	i--Civil Engineering	n--Geology
c--Agronomy	g--Graduate courses	k--Electrical Engineering	r--Irrigation and drainage

College or University, Address	Geodesy			Seismology			Meteorology		
	u	g	P	u	g	P	u	g	P
ALASKA									
University of Alaska College	+	..	in sF	+	..	O	+	..	O
ARKANSAS									
University of Arkansas Fayetteville	..	..	..	..	..	..	+	+	n-l
CALIFORNIA									
College of the Pacific Stockton	+	..	a el	+	..	n	+	..	al
Occidental College Los Angeles	..	..	..	..	..	..	..	..	..
Stanford University Stanford University	..	..	..	+	..	t	..	..	..
COLORADO									
University of Denver Denver	+	..	es	..	..	..	+	..	lF
CONNECTICUT									
Yale University New Haven	+	+	i	+	+	n	+	..	F
DISTRICT OF COLUMBIA									
Georgetown University Washington	..	+	e	..	+	L	+	..	F
GEORGIA									
Emory University Emory University	..	..	..	..	..	..	+	..	n
Mercer University Macon	..	..	..	..	..	..	+	..	F
ILLINOIS									
University of Chicago Chicago	+	+	en	..	+	n	+	+	lx
INDIANA									
Valparaiso University Valparaiso	..	..	..	..	..	..	+	..	l-n
De Pauw University Greencastle	..	..	..	..	..	..	+	..	l-n
MARYLAND									
University of Maryland College Park	..	..	..	..	..	..	+	..	F
MASSACHUSETTS									
Massachusetts State College Amherst	..	..	..	+	..	?	+	..	s

These have been tabulated and are given in Table 1. It is believed that the list is now substantially complete as it relates to institutions in the United States.

With regard to the data given, we repeat the statement that one should use Table 1 as a guide only, and not make selection of a school before consulting college catalogues or college authorities. In many instances work is given in one of the specialties of the branch, but no comprehensive program is offered for the branch as a whole, but a cross (+) is entered appropriately in the Table. Similarly, work in a particular branch is sometimes given as part of a general course in another field, as, for example, some fundamentals of seismology in a general course in geology. Notation (+) is made in the appropriate column in these instances. The American Geophysical Union (5241 Broad Branch Road, N. W., Washington 15, D. C.) offers aid with regard to specific questions.

and Territories, offering courses in branches of Geophysics

s--Mathematics
t--Mechanical Engineering
u--Undergraduate courses
x--Meteorology
F--Physics
J--Zoology
K--Marine
L--Seismology
M--Engineering
N--Applied Science
O--Operating station
P--Department in which courses are offered

T. M. and E.			Oceanography			Volcanology			Hydrology			Tectonophysics			Geophys. Prosp.		
u	g	P	u	g	P	u	g	P	u	g	P	u	g	P	u	g	P
+	..	kF	..	..	..	..	..	..	+	..	bi	..	..	..	+	..	nF
Other branches touched upon in general courses in geology												..	..	..	..	..	..
+	..	F	+	+	nJ	+	..	n	+	..	n	+	..	n	..	..	..
+	..	F	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
..	..	..	+	+	n K	+	+	n	+	+	n i	+	+	n	Plans developing		
+ +	..	kF	..	..	..	+	..	n	..	..	..	..	..	..	..	..	..
+	+	F	..	+	J	+	+	n	+	+	i	+	+	n	..	..	..
+	+	F	..	+	sF	..	+	L	..	..	..	..	..	..	..	..	..
+	+	kF	..	..	..	+	..	n	..	+	n	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
..	..	..	+	+	x	+	+	n	+	+	nx	+	+	n	..	+	n
..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
+	+	F	..	..	..	..	..	..	..	..	..	+	+	F	..	..	..
+	..	F	+	..	?	+	..	?	+	..	?	+	..	?	..	..	..

Table 1--Educational Institutions, listed according to States

Key to symbols:

a--Aeronautics
b--Agriculture
c--Agronomy
e--Astronomy
f--Biology
g--Graduate courses
h--Chemistry
i--Civil Engineering
k--Electrical Engineering
l--Geography
n--Geology
r--Irrigation and drainage

College or University, Address	Geodesy			Seismology			Meteorology		
	u	g	P	u	g	P	u	g	P
MICHIGAN									
Detroit Institute of Technology									
Detroit	+	..	M	..	..	..	+	..	M
MINNESOTA									
Carleton College									
Northfield	+	..	e	+	..	n	+	..	e
MISSISSIPPI									
University of Mississippi			en						
University	+	..	M	+	..	n	+	..	F
MISSOURI									
Washington University									
St. Louis	..	..	..	+	..	n	+	..	l
NEW YORK									
City College of the City of New York			i						n
New York	+	+	n	+	..	n	+	..	F
Columbia UniversityΦ			ei						
New York	+	+	n	..	+	n	+	+	n
OHIO									
Capital University									
Columbus	+	..	s	+	..	n	+	..	l
Muskinjum College									n
New Concord	+	..	s	+	..	n	+	..	F
Oberlin College									
Oberlin	..	..	..	..	..	..	+	..	l
PENNSYLVANIA									
Carnegie Institute of Technology									
Pittsburgh	..	..	..	..	..	..	..	..	..
SOUTH DAKOTA									
University of South Dakota									
Vermillion	+	..	N	..	..	..	+	..	n
TEXAS									
Baylor University									
Waco	+	..	s	..	..	..	..	..	..
Southern Methodist University									
Dallas	..	..	..	..	..	..	+	..	?
Texas College of Arts and Industries									
Kingsville	..	..	..	..	..	..	+	..	F
Texas College of Mines									
El Paso	..	..	..	..	..	..	..	..	..
UTAH									
Utah State Agricultural College									
Logan	+	..	i	..	..	..	..	..	..
VIRGINIA									
Washington and Lee University									
Lexington	..	..	..	+	..	n	+	..	F
WISCONSIN									
Beloit College									
Beloit	+	..	n	+	..	n	+	..	n
University of Wisconsin						n			
Madison	..	..	..	+	+	F	..	..	..
WYOMING									
University of Wyoming									
Laramie	+	..	i	+	..	n	+	..	x

ΦCorrection of information previously published [Education in Geophysics, *Trans*. Amer.

and Territories, offering courses in branches of Geophysics (concluded)

s--Mathematics
t--Mechanical Engineering
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T. M. and E			Oceanography			Volcanology			Hydrology			Tectonophysics			Geophys. Prosp.		
u	g	P	u	g	P	u	g	P	u	g	P	u	g	P	u	g	P
+	..	M	..	..	..	..	..	..	+	..	M	..	..	..	..	..	..
..	..	..	..	..	..	+	..	n	..	..	..	..	..	..	..	..	..
+	..	F	..	..	..	+	..	n	+	..	M	+	..	n	+	..	n F
..	..	..	..	..	..	+	+	n	+	..	n	+	+	n	+	..	n
+	+	k F	+	..	f n	+	..	n	+	+	i n	+	..	n	+	..	n
+	+	n F	+	+	n	..	+	n	+	+	i	..	+	n	..	+	n
+	..	F	+	..	n	+	..	n	+	..	n	+	..	n	..	..	..
+	..	F	+	..	n	+	..	n	+	..	n	+	..	n	+	..	n
..	..	..	..	..	..	+	..	n	+	+	n	..	..	..	..	..	..
+	..	F	..	..	..	..	..	..	..	+	i	..	..	..	..	..	..
+	..	F	+	..	n	+	..	n	+	..	n N	+	..	n	..	..	..
+	..	F	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

Some courses in geology and physics include material on fundamentals of geophysics

..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	F
..	..	..	..	..	..	+	..	n	..	..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	+	..	r M	..	..	..	..	..	..
..	..	..	+	..	n	+	..	n	..	..	..	..	..	..	..	..	..
+	..	F	+	..	f n	+	..	n	+	..	n	+	..	n	+	..	n F
..	+	n F	..	..	..	..	..	..	+	+	bi n	..	+	n F	+	+	n F
+	+	k F	..	..	..	+	+	n	+	+	i n	+	+	n	+	..	n

Geophys. Union, v. 26, pp. 70-71, 1945].

SECTION ACTIVITIES

Section of Hydrology

Third Meeting of the Washington Group--Forty-six members and guests attended a luncheon in the South Building, United States Department of Agriculture, Washington, D. C. on June 17, 1946. Walter C. Lowdermilk described the technical and social aspects of the proposed Jordan Valley Authority in Palestine and Trans-Jordan, which region, in many climatic and physical characteristics resembles Southern California and can be similarly intensively developed through use of Jordan and Mediterranean waters. Following the interesting account there were many questions, following which the meeting adjourned at 13^h45^m.

BERNARD FRANK, Secretary

SPECIAL ANNOUNCEMENTS

Nomination and election procedures--Attention is called to the Report of the Committee on Nominations published on pages 612 and 613 of this issue, and especially to the questionnaire (see page 613), on which the advice of all members is requested. As indicated in the minutes of the Executive Committee on page 610, the Committee on Nominations has prepared a questionnaire to secure a cross section of opinion of the members with regard to number of nominees and the method of their selection, in order to implement elections by mail ballot as provided in the Statutes and By-Laws as revised in July 1945. Please go over this material, mark the ballot provided on the back fly-leaf, and forward it to the Office of the Union at once, so that the Committee may have the benefit of your thoughts in this regard. All such ballots should be mailed by September 15, 1946.

Back issues of Transactions needed--Libraries, both domestic and foreign, frequently call for back issues of the *Transactions* in order to build or complete their sets. There is especially a shortage of those predating 1939, Part 1 of 1939, and Parts 3 and 4 of 1944. The Union will be grateful for the return of issues for which members have no further need. *Transactions* of 1944 and earlier should be sent Book Post (four cents for the first pound, and three cents for each additional pound); those of 1945 and later should be sent at magazine rates (one cent for two ounces). The Union will be glad to refund postage.

Look for Special Announcements here--Attention is again called to the fact that this last page of each issue is utilized for such special announcements as may be pertinent. With the issuance of the *Transactions* as a bimonthly, notices regarding nominations, elections, and other pertinent matters will be published here, rather than forwarded to the membership by separate letters. Get the habit of looking on the last page of each issue for word of these special matters.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 27 OCTOBER 1946 Number V

PRELIMINARY DETERMINATION OF THE DIMENSION OF THE EARTH FROM THE RESULTS OF CHINESE TRIANGULATION

Yung-Ling Chen

The Central Land Surveying Bureau of China established several arcs of principal triangulation during 1932-37. Those which were completed before the outbreak of the war in July, 1937, are Nanking-Anking, Nanking-Hsüchow, Anking-Nanchang, Nanchang-Kiukiang, and Anking-Wuchang arcs.

At the end of each arc, a base line was measured with invar tapes or wires and an astronomical station at which latitude, longitude, and the azimuth to an adjacent station were determined by astronomical observations. The methods used in the astronomical determinations were the same as those used by the United States Coast and Geodetic Survey, that is, latitude by the Talcott method, longitude by wireless time-signals, and azimuth by observing Polaris. The probable errors of these astronomical determinations were below ± 0.″1 for determinations of latitude, ± 0.″1 for determinations of longitude, and ± 0.″4 for determinations of azimuth.

In the calculation of these triangulation arcs, each was adjusted separately. In addition to the angle and side conditions, the length condition (that is, the base-line condition) was included. The Laplace azimuth condition was not used in the adjustment.

After the triangulation arcs had been adjusted, the geodetic positions of all stations were computed on the Hayford Ellipsoid (1910), which has an equatorial semi-diameter of 6,378,388 meters and a compression of 1:297.0. Station Nanking was adopted as the origin, with the following geographical coordinates, which are identical with the results of the precise astronomical determinations: Latitude, 32°03′26.″468; longitude, 118°46′56.″415; azimuth to "Purple Hill," 72°37′22.″19.

The results of the computed geodetic positions of all Laplace stations with the corresponding values obtained directly from the astronomical determinations are shown in Table 1.

Table 1--Astronomical and geodetic latitudes, longitudes, and azimuths of the Laplace stations

Station	Method	Latitude	Longitude	Azimuth	
				To station	
		° ′ ″	° ′ ″		° ′ ″
Nanking	Astr.	32 03 26. 468	118 46 56. 415	Purple Hill	72 37 22. 19
	Geod.	32 03 26. 468	118 46 56. 415		72 37 22. 19
Hsüchow	Astr.	34 06 29. 155	117 12 50. 610	Base West	73 22 51. 49
	Geod.	34 06 26. 274	117 12 52. 164		73 22 51. 84
Fangshan	Astr.	31 53 58. 372	118 51 60. 346	Chihshan	103 35 16. 61
	Geod.	31 53 57. 060	118 51 57. 054		103 35 14. 08
Anking	Astr.	30 29 08. 393	117 02 45. 405	Taochialing	193 31 32. 18
	Geod.	30 29 05. 409	117 02 46. 121		193 31 26. 24
Nanchang	Astr.	28 41 14. 067	115 53 41. 010	Leyshan	117 46 39. 06
	Geod.	28 41 10. 840	115 53 41. 188		117 46 37. 55
Shershan	Astr.	30 32 44. 218	114 18 07. 680	Möhshan	85 23 31. 78
	Geod.	30 32 41. 509	114 18 09. 237		85 23 22. 46

Since the Laplace azimuth conditions were not used in the adjustment of the triangulation, the next thing to do is to readjust the whole system using these conditions in order to obtain a unique value for the prime vertical component of the deviation of vertical at each station, either through the difference of geodetic and astronomical longitudes or through the difference of geodetic and astronomical azimuths.

If the ordinary least-square method were followed in this adjustment, it would involve an enormous amount of computing which might require a number of years for completion. However, for our purpose here, an approximate method will suffice. In this method each arc of triangulation between the Laplace stations will be replaced by a geodetic line, the length and azimuth of which are computed from the geodetic coordinates of the end stations. While the lengths of these geodetic lines may be considered as adjusted, since the base-line conditions were included in the adjustment of the triangulation arcs, their azimuths are still subject to the errors of triangulation and must be corrected according to the Laplace azimuth conditions. This could be done very simply if the deviation of vertical at the origin should be considered as zero. But in solving our problem of determining the dimension of the ellipsoid which fits the surveyed region best, the deviation of vertical at the origin must also be taken into account, for a change of the geodetic coordinates of the origin will not only affect the coordinates of all other stations, but also in turn affect their Laplace equations. Hence additional terms due to the effect of the deviation of vertical at the origin and the change of the dimension of the reference ellipsoid must be added to the Laplace azimuth equations at the very beginning.

In the following adjustment the values of astronomical latitudes and longitudes will be considered as free from errors, for they are by far more accurate than those derived from our limited geodetic computations. But it is somewhat different in the case of astronomical azimuths. The azimuth between two Laplace stations could not be directly determined by astronomical observations. It can be deduced from the astronomical azimuth directly observed to an adjacent station by adding to it the annexing angle between this direction and the direction of the geodetic line joining the Laplace stations. While the observed astronomical azimuth may be considered as free of errors, the annexing angle, however, will be changed when the triangulation is readjusted according to the Laplace conditions. Hence, to each of the astronomical azimuths a correction due to the annexing angle must be added. These corrections are the unknowns to be determined in the readjustment.

Let i and k be two consecutive Laplace stations joined by a geodetic line, φ_i, λ_i and φ_k, λ_k the geodetic latitude and longitude of the stations i and k, respectively, $\Delta\varphi_i$, $\Delta\lambda_i$ and $\Delta\varphi_k$, $\Delta\lambda_k$ the corrections to φ_i, λ_i and φ_k, λ_k, respectively, obtained from the adjustment, α_{ik} and α_{ki} the geodetic azimuth and reverse azimuth of the geodetic line ik, $\Delta\alpha_{ik}$ and $\Delta\alpha_{ki}$ their corrections, $\varphi_{i'}$, $\lambda_{i'}$, and $\varphi_{k'}$, $\lambda_{k'}$ the astronomical latitude and longitude of the stations i and k, respectively, $\alpha_{i'k}$ and $\alpha_{k'i}$ the astronomical azimuth and reverse azimuth of the geodetic line ik, ΔA_{ik} and ΔA_{ki} the corrections to the annexing angles A_{ik} and A_{ki} in deducing $\alpha_{i'k}$ and $\alpha_{k'i}$. Further let the meridian and the prime vertical components of the deviations of vertical at i and k be denoted by ξ_i, η_i and ξ_k, η_k, respectively. Then after the adjustment, the equations (1) and (2) must be fulfilled for stations i and k.

Station i:

$$\left.\begin{aligned} &\varphi_i + \Delta\varphi_i + \xi_i = \varphi_{i'} \\ &\lambda_i + \Delta\lambda_i + \eta_i \sec\varphi_i = \lambda_{i'} \\ &\alpha_{ik} + \Delta\alpha_{ik} + \eta_i \tan\varphi_i = \alpha_{i'k} + \Delta A_{ik} \end{aligned}\right\} \dots\dots\dots\dots\dots (1)$$

Station k:

$$\left.\begin{aligned} &\varphi_k + \Delta\varphi_k + \xi_k = \varphi_{k'} \\ &\lambda_k + \Delta\lambda_k + \eta_k \sec\varphi_k = \lambda_{k'} \\ &\alpha_{ki} + \Delta\alpha_{ki} + \eta_k \tan\varphi_k = \alpha_{k'i} + \Delta A_{ki} \end{aligned}\right\} \dots\dots\dots\dots\dots (2)$$

From (1) we can write

$$\left.\begin{aligned} &\Delta\varphi_i = (\varphi_{i'} - \varphi_i) - \xi_i \\ &\Delta\lambda_i = (\lambda_{i'} - \lambda_i) - \eta_i \sec\varphi_i \\ &\Delta\alpha_{ik} = (\alpha_{i'k} - \alpha_{ik}) + \Delta A_{ik} - \eta_i \tan\varphi_i \end{aligned}\right\} \dots\dots\dots\dots\dots (3)$$

From (2) we can write

$$\left.\begin{aligned} &\xi_k = (\varphi_{k'} - \varphi_k) - \Delta\varphi_k \\ &\eta_k = [(\lambda_{k'} - \lambda_k) - \Delta\lambda_k] \cos\varphi_k \\ &\eta_k = [(\alpha_{k'i} - \alpha_{ki}) + \Delta A_{ki} - \Delta\alpha_{ki}] \cot\varphi_k \end{aligned}\right\} \dots\dots\dots\dots\dots (4)$$

In the above equations the corrections $\Delta\varphi_k$, $\Delta\lambda_k$, and $\Delta\alpha_{ki}$, to the geodetic coordinates of k are dependent on the corrections $\Delta\varphi_i$, $\Delta\lambda_i$, and $\Delta\alpha_{ik}$ on the one hand, and on the change of the dimension of the Earth on the other hand. Let the equatorial semi-diameter and the compression of the Hayford ellipsoid be denoted by a and f, and the corrections to them by Δa and Δf, respectively. The relations of the corrections $\Delta\varphi_k$, $\Delta\lambda_k$, and $\Delta\alpha_{ki}$, respectively, to the corrections $\Delta\varphi_i$, $\Delta\lambda_i$, $\Delta\alpha_{ik}$, Δa, and Δf may then be written

$$\left.\begin{aligned}
\Delta\varphi_k &= (\partial\varphi_k/\partial\varphi_i)\,\Delta\varphi_i + (\partial\varphi_k/\partial\alpha_{ik})\,\Delta\alpha_{ik} + (\partial\varphi_k/\partial a)\,\Delta a + (\partial\varphi_k/\partial f)\,\Delta f\\
\Delta\lambda_k &= (\partial\lambda_k/\partial\varphi_i)\,\Delta\varphi_i + \Delta\lambda_i + (\partial\lambda_k/\partial\alpha_{ik})\,\Delta\alpha_{ik} + (\partial\lambda_k/\partial a)\,\Delta a + (\partial\lambda_k/\partial f)\,\Delta f\\
\Delta\alpha_{ki} &= (\partial\alpha_{ki}/\partial\varphi_i)\,\Delta\varphi_i + (\partial\alpha_{ki}/\partial\alpha_{ik})\,\Delta\alpha_{ik} + (\partial\alpha_{ki}/\partial a)\,\Delta a + (\partial\alpha_{ki}/\partial f)\,\Delta f
\end{aligned}\right\}\;..\;(5)$$

The differential coefficients in the above equations are [JORDAN-EGGERT, 1923]

$$\left.\begin{aligned}
(\partial\varphi_k/\partial\varphi_i) &= (M_i/M_k)\cos(\lambda_k - \lambda_i)\\
(\partial\varphi_k/\partial\alpha_{ik}) &= (m/M_k)\sin\alpha_{ki}\\
(\partial\varphi_k/\partial a) &= (\rho/aM_k)\,s\cos\alpha_{ki}\\
(\partial\lambda_k/\partial\varphi_i) &= (M_i/N_k)[\sin(\lambda_k - \lambda_i)/\cos\varphi_k]\\
(\partial\lambda_k/\partial\alpha_{ik}) &= (m/N_k)(\cos\alpha_{ki}/\cos\varphi_k)\\
(\partial\lambda_k/\partial a) &= (\rho s/aN_k)(\sin\alpha_{ki}/\cos\varphi_k)\\
(\partial\alpha_{ki}/\partial\varphi_i) &= [\sin(\lambda_k - \lambda_i)/\cos\varphi k](1 - e^2\sin^2\varphi_k\cos^2\varphi_k)\\
(\partial\alpha_{ki}/\partial\alpha_{ik}) &= (dm/ds) - (m/N_k)\cos\alpha_{ki}\tan\varphi_k\\
(\partial\alpha_{ki}/\partial a) &= (\rho/aN_k)\,s\sin\alpha_{ki}\tan\varphi_k\\
(\partial\varphi_k/\partial f) &= (\varphi_k - \varphi_i)(2 - 3\sin^2\varphi) + [(\lambda_k - \lambda_i)^2/2f]\sin^3\varphi\cos\varphi\\
(\partial\lambda_k/\partial f) &= -(\lambda_k - \lambda_i)\sin^2\varphi_i(\cos\varphi_i/\cos\varphi_k)\\
(\partial\alpha_{ki}/\partial f) &= (\lambda_k - \lambda_i)\cos\varphi_i[(\varphi_k - \varphi_i)\cos^2\varphi_i - \sin^2\varphi_i\tan\varphi_k]
\end{aligned}\right\}\;\ldots\ldots\ldots\;(6)$$

in which M_i, M_k = meridian radius of curvature at points i and k, respectively, N_k = prime-vertical radius of curvature at point k, $\varphi = [(\varphi_1 + \varphi_2)/2]$, s = length of the geodetic line joining points i and k, m = reduced length of the geodetic line ik, e = ellipticity of the Hayford ellipsoid.

Substituting (3) into (5), and then into (4), the components of the deviation of vertical at station k result as in (7).

$$\left.\begin{aligned}
\xi_k = {} & [(\varphi_{k'} - \varphi_k) - (\partial\varphi_k/\partial\varphi_i)(\varphi_{i'} - \varphi_i) - (\partial\varphi_k/\partial\alpha_{ik})(\alpha_{i'k} - \alpha_{ik})]\\
& - (\partial\varphi_k/\partial\alpha_{ik})\,\Delta A_{ik} + (\partial\varphi_k/\partial\varphi_i)\;\xi_i + (\partial\varphi_k/\partial\alpha_{ik})\tan\varphi_i\,\eta_i\\
& - (\partial\varphi_k/\partial a)\,\Delta a - (\partial\varphi_k/\partial f)\,\Delta f\\[1ex]
\eta_k = {} & \cos\varphi_k[(\lambda_{k'} - \lambda_k) - (\lambda_{i'} - \lambda_i) - (\partial\lambda_k/\partial\varphi_i)(\varphi_{i'} - \varphi_i)\\
& - (\partial\lambda_k/\partial\alpha_{ik})(\alpha_{i'k} - \alpha_{ik})] - (\partial\lambda_k/\partial\alpha_{ik})\cos\varphi_k\Delta A_{ik}\\
& + (\partial\lambda_k/\partial\varphi_i)\cos\varphi_k\;\xi_i + [(\cos\varphi_k/\cos\varphi_i) + (\partial\lambda_k/\partial\alpha_{ik})(\tan\varphi_i/\sec\varphi_k)]\eta_i\\
& - (\partial\lambda_k/\partial a)\cos\varphi_k\,\Delta a - (\partial\lambda_k/\partial f)\cos\varphi_k\,\Delta f\\[1ex]
\eta_k = {} & \cot\varphi_k[(\alpha_{k'i} - \alpha_{ki}) - (\partial\alpha_{ki}/\partial\varphi_i)(\varphi_{i'} - \varphi_i) - (\partial\alpha_{ki}/\partial\alpha_{ik})(\alpha_{i'k} - \alpha_{ik})]\\
& - (\partial\alpha_{ki}/\partial\alpha_{ik})\cot\varphi_k\,\Delta A_{ik} + \cot\varphi_k\,\Delta A_{ki} + (\partial\alpha_{ki}/\partial\varphi_i)\cot\varphi_k\,\xi_i\\
& + (\partial\alpha_{ki}/\partial\alpha_{ik})(\tan\varphi_i/\tan\varphi_k)\eta_i - (\partial\alpha_{ki}/\partial a)\cot\varphi_k\,\Delta a\\
& - (\partial\alpha_{ki}/\partial f)\cot\varphi_k\Delta f
\end{aligned}\right\}(7)$$

Using $\ell_1, \ell_2, \ldots, m_1, m_2, \ldots, n_1, n_2, \ldots$, and w_ℓ, w_m, w_n, to denote the coefficients, (7) may be reduced to

$$\left.\begin{aligned}
\xi_k &= \ell_1\Delta A_{ik} && + \ell_3\xi_i + \ell_4\eta_i + \ell_5(\Delta a/a) + \ell_6\Delta f + w_\ell\\
\eta_k &= m_1\Delta A_{ik} + m_2A_{ik} && + m_3\,\xi_i + m_4\eta_i + m_5(\Delta a/a) + m_6\Delta f + w_m\\
\eta_k &= n_1\Delta A_{ik} + n_2\Delta A_{ik} && + n_3\xi_i + n_4\eta_i + n_5(\Delta a/a) + n_6\Delta f + w_n
\end{aligned}\right\}\;\ldots\ldots\ldots\;(8)$$

The expressions for the coefficients which may be derived from equation (6) are

$$\left.\begin{aligned}
\ell_1 &= -(m/M_k)\sin\alpha_{ki}\\
\ell_3 &= +(M_1/M_k)\cos(\lambda_k - \lambda_i)\\
\ell_4 &= +(m/M_k)\sin\alpha_{ki}\tan\varphi_i\\
\ell_5 &= -(\rho/M_k)\,s\cos\alpha_{ki}\\
\ell_6 &= -(\varphi_k - \varphi_i)(2 - 3\sin^2\varphi) - (1/2\rho)(\lambda_k - \lambda_i)^2\sin^3\varphi\cos\varphi\\
m_1 &= +(m/N_k)\cos\alpha_{ki}\\
m_3 &= +(M_i/M_k)\sin(\lambda_k - \lambda_i)\sin\varphi_k
\end{aligned}\right\}\;\ldots\ldots\;(9)$$

$$\left.\begin{aligned}
m_4 &= +\,(\cos\varphi_k/\cos\varphi_i) - m_1\tan\varphi_i\\
m_5 &= -\,(\rho/N_k)\, s\sin\alpha_{ki}\\
m_6 &= +\,(\lambda_k-\lambda_i)\sin^2\varphi_i\cos\varphi_i\\
n_1 &= m_1 - (dm/ds)\cot\varphi_k\\
n_2 &= \cot\varphi_k\\
n_3 &= +\,[\sin(\lambda_k-\lambda_i)/\sin\varphi_k](1-e^2\sin^2\varphi_k\cos^2\varphi_k)\\
n_4 &= -\,n_1\tan\varphi_i\\
n_5 &= m_5\\
n_6 &= (\lambda_k-\lambda_i)\cos\varphi_i[\sin^2\varphi_i-(\varphi_k-\varphi_i)\cos^2\varphi_i\cot\varphi_k]\\
w_\ell &= (\varphi_{k'}-\varphi_k)-\ell_3(\varphi_{i'}-\varphi_i)+\ell_1(\alpha_{i'k}-\alpha_{ik})\\
w_m &= (\lambda_{k'}-\lambda_k)\cos\varphi_k-(\lambda_{i'}-\lambda_i)\cos\varphi_k-m_3(\varphi_{i'}-\varphi_i)+m_\ell(\alpha_{i'k}-\alpha_{ik})\\
w_n &= (\alpha_{k'i}-\alpha_{ki})\cot\varphi_k-n_3(\varphi_{i'}-\varphi_i)+n_1(\alpha_{i'k}-\alpha_{ik})
\end{aligned}\right\}\quad \text{(9, concluded)}$$

Equating the right-hand sides of the second and third equations in (8) and noting the relation of the coefficients in (9), we get, for the geodetic line ik, the Laplace condition (10).

$$(m_1-n_1)\,\Delta A_{ik}-\cot\varphi_k\Delta A_{ki}+(m_3-n_3)\xi_i+(m_4-n_4)\eta_i+(m_6-n_6)\,\Delta f+(w_m-w_n)=0\quad .\ (10)$$

This is the final form of the Laplace condition between stations i and k. The sequence of calculation is: (1) To calculate, from the geodetic latitudes and longitudes of the successive Laplace stations, the lengths and azimuths of the geodetic lines joining them. (2) To calculate the coefficients ℓ, m, and n and the constants w, according to (9), and then to establish the equations for the components of the deviation of vertical of each station. (3) To form the Laplace conditions according to (10). The results of these calculations for the Laplace stations given in Table 1, are shown in Tables 2, 3, 4, and 5. Table 2 and Table 3 are self-evident. The equations in Table 4 are formed by eliminating ξ_3 and η_3 from the equations of ξ_4, η_4 and ξ_5, η_5 in Table 3, so that only the terms consisting ξ_0, η_0 are present in the resultant Laplace conditions. The Laplace conditions given in Table 5 are formed by equating the two equations for η given in Tables 3 and 4.

Table 2--The lengths and azimuths of the geodetic lines

Geod. line	Log length, s	Azimuth		Reverse azimuth	
		Geodetic	Astr.	Geodetic	Astr.
		° ′ ″	″	° ′ ″	″
0-1	5.43200506	327 38 53. 862	53. 862	146 47 32. 354	32. 004
0-2	4.28405924	155 44 52. 657	52. 657	335 47 31. 875	34. 405
0-3	5.38072418	223 56 06. 882	06. 882	43 02 01. 942	07. 882
3-4	5.42066442	272 08 38. 107	44. 047	90 45 02. 287	03. 797
3-5	5.35877475	209 30 54. 543	60. 483	28 56 47. 789	57. 109

Note: The astronomical azimuths and reverse azimuths are obtained by adding to the respective geodetic values the difference in astronomical and geodetic azimuths given in Table 1.

Table 3--Equations of the deviations of verticals

Station 1 (Hsüchow)

Comp.	$\Delta A_{0.1}$	$\Delta A_{1.0}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
ξ_1 =	- 0.0233	. . . . .	+ 0.9993	+ 0.0146	+ 7342	- 7391	+ 2.″881
η_1 =	- 0.0363	. . . . .	- 0.0152	+ 0.9996	- 4895	- 1379	- 1. 287
η_1 =	- 1.5116	+ 1.4766	- 0.0498	+ 0.9467	- 4895	- 1560	- 0. 517

Station 2 (Fangshan)

Comp.	$\Delta A_{0.2}$	$\Delta A_{2.0}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
ξ_2 =	+ 0.0012	. . . . .	+ 1.0000	- 0.0008	- 570	+ 661	+ 1.″332
η_2 =	+ 0.0070	. . . . .	+ 0.0008	+ 1.0000	+ 255	+ 72	+ 2. 794
η_2 =	- 1.5996	+ 1.6066	+ 0.0018	+ 1.0018	+ 255	+ 71	+ 4. 064

Table 3--Equations of the deviations of verticals (concluded)

Station 3 (Anking)

Comp.	$\Delta A_{0.3}$	$\Delta A_{3.0}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
$\xi_3 =$	- 0.0258	.....	+ 0.9998	+ 0.0162	- 5703	+ 6735	+ 2″.984
$\eta_3 =$	+ 0.0275	.....	+ 0.0153	+ 0.9996	- 5298	- 1493	- 0.617
$\eta_3 =$	- 1.6700	+ 1.6987	- 0.0596	+ 1.0459	- 5298	- 1315	+10.090

Station 4 (Nanchang)

Comp.	$\Delta A_{3.4}$	$\Delta A_{4.3}$	ξ_3	η_3	$(\Delta a/a)$	Δf	W
$\xi_4 =$	- 0.0414	.....	+ 0.9988	+ 0.0244	+ 411	- 292	- 0″.517
$\eta_4 =$	- 0.0020	.....	+ 0.0242	+ 1.0006	- 8501	- 2191	- 1.425
$\eta_4 =$	- 1.6952	+ 1.6946	- 0.0940	+ 0.9980	- 8501	- 2202	+ 6.370

Station 5 (Shershan)

Comp.	$\Delta A_{3.5}$	$\Delta A_{5.3}$	ξ_3	η_3	$(\Delta a/a)$	Δf	W
$\xi_5 =$	- 0.0174	.....	+ 1.0001	+ 0.0102	- 6493	+ 8211	+ 0″.140
$\eta_5 =$	+ 0.0313	.....	+ 0.0096	+ 0.9994	- 3572	- 919	+ 0.001
$\eta_5 =$	- 1.7952	+ 1.8276	- 0.0418	+ 1.0568	- 3672	- 768	- 7.780

Table 4--Reformed equations of the deviations of verticals at stations 4 and 5

Station 4 (Nanchang)

Comp.	$\Delta A_{0.3}$	$\Delta A_{3.4}$	$\Delta A_{4.3}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
$\xi_4 =$	- 0.0251	- 0.0414	.....	+ 0.9990	+ 0.0406	- 5414	+ 6399	+ 2″.448
$\eta_4 =$	+ 0.0269	- 0.0020	.....	+ 0.0395	+ 1.0006	- 13940	- 3522	- 1.970
$\eta_4 =$	+ 0.0298	- 1.6952	+ 1.6946	- 0.0787	+ 0.9961	- 13252	- 4325	+ 5.474

Station 5 (Shershan)

Comp.	$\Delta A_{0.3}$	$\Delta A_{3.5}$	$\Delta A_{5.3}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
$\xi_5 =$	- 0.0255	- 0.0174	.....	+ 1.0001	+ 0.0264	- 12250	+ 14932	+ 3″.118
$\eta_5 =$	+ 0.0273	+ 0.0313	.....	+ 0.0249	+ 0.9992	- 8920	- 2346	- 0.587
$\eta_5 =$	+ 0.0302	- 1.7952	+ 1.8276	- 0.0256	+ 1.0557	- 8933	- 2628	- 8.557

Table 5--Laplace conditions

No.	$\Delta A_{0.1}$	$\Delta A_{1.0}$	$\Delta A_{0.2}$	$\Delta A_{2.0}$	$\Delta A_{0.3}$	$\Delta A_{3.0}$	$\Delta A_{3.4}$	$\Delta A_{4.3}$	$\Delta A_{3.5}$	$\Delta A_{5.3}$	ξ_0	η_0	$(\Delta a/a)$	Δf	W
1	+ 1.4753	- 1.4766	.....	.....	.....	.....	.....	.....	.....	.....	+ 0.0346	+ 0.0529	...	+ 181	- 0″.770 = 0
2	.....	.....	+ 1.6066	- 1.6066	.....	.....	.....	.....	.....	.....	- 0.0010	- 0.0018	...	+ 1	- 1.270 = 0
3	.....	.....	.....	.....	+ 1.6975	- 1.6987	.....	.....	.....	.....	+ 0.0749	- 0.0463	...	- 178	-10.707 = 0
4	.....	.....	.....	.....	- 0.0029	.....	+ 1.6932	- 1.6946	.....	.....	+ 0.1182	+ 0.0045	- 688	+ 803	- 7.444 = 0
5	.....	.....	.....	.....	- 0.0029	.....	.....	.....	+ 1.8265	- 1.8276	+ 0.0505	- 0.0565	+ 13	+ 282	+ 7.970 = 0

In the Laplace conditions (Table 5), the values of w are constants, of ΔA are quantities to be determined in the adjustment, and the unknowns ξ_0, η_0, $(\Delta a/a)$, and Δf will remain to be determined later in finding the most favorable dimension of the ellipsoid. With the conditions in Table 5, the most probable values of ΔA are found, by the method of least squares, to be

$$\left.\begin{array}{l}
\Delta A_{0.1} = -\ 0.0117\ \xi_0 -\ 0.0179\ \eta_0 \qquad\qquad\qquad\quad -\ 61\Delta f + 0.''261 \\
\Delta A_{1.0} = +\ 0.0117\ \xi_0 +\ 0.0179\ \eta_0 \qquad\qquad\qquad\quad +\ 61\Delta f -\ 0.''261 \\
\Delta A_{0.2} = +\ 0.0003\ \xi_0 +\ 0.0006\ \eta_0 \qquad\qquad\qquad\qquad\qquad\quad +\ 0.''395 \\
\Delta A_{2.0} = -\ 0.0003\ \xi_0 -\ 0.0006\ \eta_0 \qquad\qquad\qquad\qquad\qquad\quad -\ 0.''395 \\
\Delta A_{0.3} = -\ 0.0219\ \xi_0 +\ 0.0136\ \eta_0 \qquad\qquad\qquad\quad +\ 53\Delta f +\ 3.''152 \\
\Delta A_{3.0} = +\ 0.0221\ \xi_0 -\ 0.0136\ \eta_0 \qquad\qquad\qquad\quad -\ 52\Delta f -\ 3.''154 \\
\Delta A_{3.4} = -\ 0.0349\ \xi_0 -\ 0.0013\ \eta_0 + 203\ (\Delta a/a) -\ 237\Delta f +\ 2.''199 \\
\Delta A_{4.3} = +\ 0.0349\ \xi_0 +\ 0.0013\ \eta_0 -\ 203\ (\Delta a/a) +\ 237\Delta f -\ 2.''201 \\
\Delta A_{3.5} = -\ 0.0138\ \xi_0 +\ 0.0155\ \eta_0 -\ \ \ 4\ (\Delta a/a) -\ \ 77\Delta f -\ 2.''178 \\
\Delta A_{5.3} = +\ 0.0139\ \xi_0 -\ 0.0155\ \eta_0 +\ \ \ 4\ (\Delta a/a) +\ \ 77\Delta f +\ 2.''179
\end{array}\right\} \ldots\ldots (11)$$

Substituting the above equations into the equations of the deviations of verticals given in Tables 3 and 4, we get the adjusted values of the deviations at different Laplace stations:

$$\left.\begin{array}{l}
\xi_0 = +\ 1.0000\ \xi_0 \\
\eta_0 = \qquad\qquad\quad +\ 1.0000\ \eta_0 \\
\xi_1 = +\ 0.9996\ \xi_0 +\ 0.0150\ \eta_0 +\ \ 7342\ (\Delta a/a) -\ \ 7390\Delta f +\ 2.''875 \\
\eta_1 = -\ 0.0148\ \xi_0 +\ 1.0002\ \eta_0 -\ \ 4895\ (\Delta a/a) -\ \ 1377\Delta f -\ 1.''296 \\
\xi_2 = +\ 1.0000\ \xi_0 -\ 0.0008\ \eta_0 -\ \ \ 570\ (\Delta a/a) +\ \ \ 661\Delta f +\ 1.''332 \\
\eta_2 = +\ 0.0008\ \xi_0 +\ 1.0000\ \eta_0 +\ \ \ 255\ (\Delta a/a) +\ \ \ \ 72\Delta f +\ 2.''797 \\
\xi_3 = +\ 1.0004\ \xi_0 +\ 0.0158\ \eta_0 -\ \ 5703\ (\Delta a/a) +\ \ 6734\Delta f +\ 2.''903 \\
\eta_3 = +\ 0.0147\ \xi_0 +\ 1.0000\ \eta_0 -\ \ 5298\ (\Delta a/a) -\ \ 1492\Delta f -\ 0.''530 \\
\xi_4 = +\ 1.0010\ \xi_0 +\ 0.0404\ \eta_0 -\ \ 5422\ (\Delta a/a) +\ \ 6408\Delta f +\ 2.''278 \\
\eta_4 = +\ 0.0390\ \xi_0 +\ 1.0010\ \eta_0 -\ 13940\ (\Delta a/a) -\ \ 3521\Delta f -\ 1.''889 \\
\xi_5 = +\ 1.0008\ \xi_0 +\ 0.0258\ \eta_0 -\ 12250\ (\Delta a/a) +\ 14932\Delta f +\ 3.''076 \\
\eta_5 = +\ 0.0239\ \xi_0 +\ 1.0001\ \eta_0 -\ \ 8920\ (\Delta a/a) -\ \ 2347\Delta f -\ 0.''569
\end{array}\right\} \ldots\ldots (12)$$

In the above equations, the constant terms are the values of the components of the deviations with respect to the Hayford ellipsoid, when the deviation of vertical at the origin is taken as zero. The terms with ξ_0, η_0, $(\Delta a/a)$, and Δf give the corrections due to the deviation of vertical at the origin (ξ_0, η_0) and the change of the dimension of the Earth $(\Delta a, \Delta f)$.

The ellipsoid which fits the surveyed region best is that which makes the deviations of all stations a minimum. This could be obtained by introducing the condition

$$[\xi\xi] + [\eta\eta] = \text{minimum}$$

to the above equations and solving them by means of least squares. In order to make the numerical values of the coefficients in the above equations nearly of the same magnitude, two new unknowns, u and v, will be introduced instead of $(\Delta a/a)$ and Δf, as in (13).

$$u = 10{,}000\ (\Delta a/a) \qquad v = 10{,}000\ \Delta f \ \ldots\ldots\ldots\ldots\ldots (13)$$

The normal equations thus formed are

$$\left.\begin{array}{l}
+\ 6.007\ \xi_0 +\ 0.160\ \eta_0 -\ 1.738\ u +\ 2.116\ v + 12.''393 = 0 \\
+\ 0.160\ \xi_0 +\ 6.005\ \eta_0 -\ 3.333\ u -\ 0.802\ v -\ \ 1.''230 = 0 \\
-\ 1.738\ \xi_0 -\ 3.333\ \eta_0 +\ 5.923\ u -\ 2.258\ v -\ \ 0.''494 = 0 \\
+\ 2.116\ \xi_0 -\ 0.802\ \eta_0 -\ 2.258\ u +\ 3.863\ v +\ \ 7.''047 = 0
\end{array}\right\} \ldots\ldots\ldots (14)$$

The solution of this system of equations gives the following values for the unknowns: $\xi_0 = -\ 1.''821 \pm 0.''37$; $\eta_0 = -\ 1.''073 \pm 0.''49$; $u = -\ 4.873 \pm 0.55$; and $v = -\ 2.147 \pm 0.61$. Converting the

values of u and v to those of Δa and Δf by means of (13), we get $\Delta a = -1.873 \times 637.8 = -1195 \pm 350$ meters and $\Delta f = -0.0002147 \pm 0.000061$. Adding this to the Hayford values a = 6,378,388 meters and (1/f) = 297.0, the resulting dimension of the ellipsoid will be a = 6,377,193 ± 350 meters, and (1/f) = 317.2 ± 6.1.

As the geodetic measurements used in the above determination cover only a few degrees in latitude, the value of (1/f) given above could, therefore, have hardly any significance. Furthermore the results obtained either by geodetic measurement or by gravity measurement over a large part of the Earth have shown uniquely that the Hayford value 297.0 for (1/f) is the most probable one. Hence we will, in the next step, keep this value of f unchanged and determine the value of a alone. The new system of normal equations for this can be easily obtained from (14) by putting v = 0 as in (15).

$$\left.\begin{aligned} +6.007\,\xi_0 + 0.160\,\eta_0 - 1.738\,u + 12.^{\prime\prime}393 &= 0 \\ +0.160\,\xi_0 + 6.005\,\eta_0 - 3.333\,u - 1.^{\prime\prime}230 &= 0 \\ -1.738\,\xi_0 - 3.333\,\eta_0 + 5.923\,u - 0.^{\prime\prime}494 &= 0 \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots (15)$$

Solving these equations, we get: $\xi_0 = -2.^{\prime\prime}240 \pm 0.^{\prime\prime}43$; $\eta_0 = -0.^{\prime\prime}079 \pm 0.^{\prime\prime}50$; $\Delta a = -393 \pm 332$ meters; or a = 6,377,995 ± 332 meters.

This value of a is only 393 meters smaller than the Hayford value, and its probable error amounts to ± 332 meters, which is about as big as the correction Δa itself. If we leave both the corrections Δa and Δf as zero, and determine ξ_0 and η_0 alone, then we will get the following values: $\xi_0 = -2.^{\prime\prime}070 \pm 0.^{\prime\prime}45$; $\eta_0 = +0.^{\prime\prime}259 \pm 0.^{\prime\prime}44$.

In order to compare the above results, let us consider the following four cases:

Case I--Hayford ellipsoid unchanged (u = 0, v = 0), deviation of vertical at the origin taken as zero ($\xi_0 = 0$, $\eta_0 = 0$).

Case II--Hayford ellipsoid unchanged (u = 0, v = 0), deviation of vertical at the origin determined with the condition $[\xi\xi] + [\eta\eta]$ = minimum.

Case III--Hayford value of f = 1:297.0 kept unchanged, the equatorial semi-diameter of the ellipsoid, a, and the deviation of the vertical at the origin, ξ_0 and η_0, determined with the condition $[\xi\xi] + [\eta\eta]$ = minimum.

Case IV--The equatorial semi-diameter and the compression of the ellipsoid, a and f, together with the deviation of vertical at the origin, ξ_0 and η_0, determined with the condition $[\xi\xi] + [\eta\eta]$ = minimum.

The components of the deviations of verticals of all the stations are computed separately for each of the above four cases according to (13). The results are shown in Table 6.

Table 6--Values of deviations of verticals

Comp.	Case I	Case II	Case III	Case IV	III - II
	″	″	″	″	″
ξ_0	0.00	- 2.07	- 2.24	- 1.82	- 0.17
η_0	0.00	+ 0.26	- 0.08	- 1.07	- 0.34
ξ_1	+ 2.88	+ 0.81	+ 0.18	+ 1.25	- 0.63
η_1	- 1.30	- 1.01	- 1.04	- 1.13	- 0.03
ξ_2	+ 1.33	- 0.74	- 0.87	- 0.52	- 0.13
η_2	+ 2.80	+ 3.05	+ 2.70	+ 1.66	- 0.35
ξ_3	+ 2.90	+ 0.84	+ 1.01	+ 0.69	+ 0.17
η_3	- 0.53	- 0.30	- 0.32	- 0.32	- 0.02
ξ_4	+ 2.28	+ 0.22	+ 0.37	+ 0.05	+ 0.15
η_4	- 1.89	- 1.71	- 1.20	+ 0.33	+ 0.51
ξ_5	+ 3.08	+ 1.01	+ 1.59	+ 0.31	+ 0.58
η_5	- 0.57	- 0.36	- 0.15	+ 0.49	+ 0.21
$[\xi\xi] + [\eta\eta]$	46.87	20.80	19.44	11.35	.....

From Table 6 it is seen that the sum of the squares of the deviations is smallest for Case IV, and largest for Case I. The values for Case II and Case III are nearly equal. Since the determination of f in Case IV is known to be unreliable, it will be abandoned for further discussion. In Case I it has been assumed that ξ_0 and η_0 are zero, that is, the Hayford ellipsoid and the geoid are made tangent to each other at the origin. This is of course an arbitrary assumption which might be considerably contradictory to the fact. In Case II the Hayford dimension is retained, but its position with respect to the geoid is so changed as to make the sum of the squares of the deviations a minimum. In Case III the shape of the Hayford ellipsoid, f, is kept unchanged, while its dimension a is subject to a small correction. The values of the components of the deviations for Cases II and III are very close to each other; their differences are shown in the last column of Table 6. The absolute average of these differences amounts only to 0."27, which is smaller than the probable error of each of the computed deviations. Hence we may draw the conclusion that the Hayford dimension is practically the best to fit the geodetically surveyed region in China.

In the above determination of the Earth's dimension, the topographical correction has not been taken into account, for the triangulation system hitherto done covers only that part of China where the topography is mainly flat. A more detailed investigation will be necessary when a larger part of China is covered with geodetic triangulation. Yet from the result of this preliminary determination, we can already draw the following conclusions:

(1) The Hayford ellipsoid may be used with advantage in China.

(2) A meridian deviation of about - 2" should be assigned to the geodetic datum (Nanking).

Reference

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AZIMUTH DETERMINATIONS FROM NON-CIRCUMPOLAR STARS NEAR ELONGATION

F. R. Gossett and A. D. Sollins

Abstract--The method of azimuth determination from non-circumpolar stars near elongation is described, and a series of determinations by this method is compared with a series of azimuth determinations obtained from Polaris observations. The tentative conclusion is that the two methods are comparable in precision.

Astronomic parties operating in the United States have been geographically fortunate in that Polaris is readily available for their azimuth observations. Obviously, our South American colleagues are not so favored. With this geographic factor in mind, the United States Coast and Geodetic Survey decided to experiment with the method of azimuth determination by observing on non-circumpolar stars near elongation in order to evaluate its usefulness in the tropics or in the Southern Hemisphere. The location chosen for the test, therefore, was the first-order triangulation station range near Brownsville in the southernmost part of Texas.

The elongation method itself is similar to that for observations on Polaris. It consists essentially in measuring the horizontal angle between the mark and a suitable star and noting the time of the pointing on the star. The stars chosen were more than 30° from the pole, less than 45° in altitude, and in the neighborhood of elongation. The neighborhood of elongation was considered to be one during which the star's rate of change in azimuth would remain less than twice that of Polaris at culmination in middle latitudes. Both east and west stars satisfying these conditions were used. The necessary observing list can be made up using Hydrographic Office Pub. No. 214 and the American Ephemeris, if it is desired to avoid computation. All observations were made from the same tribrach on top of a standard double 25-foot wooden tower. The azimuth mark used was a fixed light on top of Brownsville Airport Tank some 13 miles from the station.

The elongation observations were obtained on nine nights by two observers, each using a Parkhurst first-order theodolite and a Wild precision theodolite. A total of 250 accepted positions were obtained, equally distributed with respect to the two observers, the two instruments, and east and west elongations. These resulted in 15 determinations when separated by night and by observer.

For control, eight Polaris determinations were obtained by three observers on seven different nights. Each determination was based on a set of observations consisting on the average of 15 position settings by the same observer.

For both types of determinations the time for each star-pointing was read to the nearest half-second from a sidereal chronometer which was controlled by radio time-signal comparisons.

The computations of the Polaris observations were made in the usual manner. The elongation observations, however, posed certain problems which will require more attention when and if the method becomes an established one. Under certain conditions, it would appear desirable to make use of the proximity of the observations to elongation. A treatment along these lines was developed recently by W. D. Lambert of the United States Coast and Geodetic Survey. For these experimental observations, however, it was found convenient to solve the astronomical triangle logarithmically, making use of an auxiliary table of addition-subtraction logarithms. Direct and reverse observations were computed separately to avoid the necessity of applying a curvature correction.

The results of the two types of azimuth observations are shown graphically in Figure 1.

The four Polaris determinations indicated by small arrows were observed about six weeks earlier than the remaining four. These last four were observed during the period of the elongation observations. In general, each elongation determination is the mean of observations on more than one star, both east and west. However, there are two determinations each based upon only one star, and three other determinations each based upon only east stars or only west stars. These are also indicated by arrows. For both Polaris and elongation, all the plotted determinations were used in computing the means which are indicated by bars.

There are other ways, of course, in which the data could be separated. Separation by instrument yielded no significant differences. Separation by east and west stars gave no conclusive evidence of the existence of a systematic difference. As indicated by the graph, however, there are discrepancies between observer and night which are large compared to the probable errors of the determinations. Even here, though, only rather tentative conclusions can be drawn.

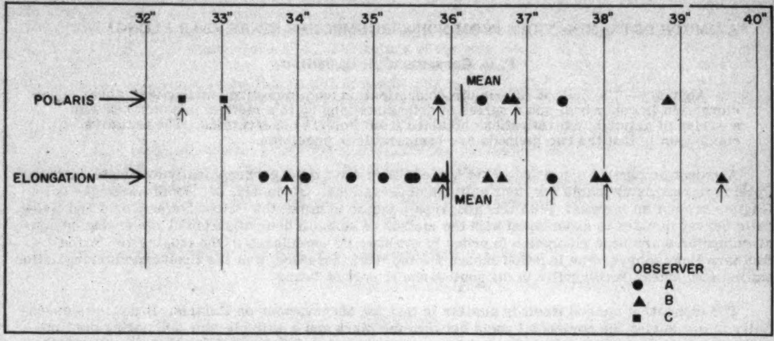

Fig. 1--Azimuths from Polaris and from non-circumpolar stars near elongation

A disturbing feature is that the Polaris determinations which were supposed to control the experiment are erratic. They have a maximum range of 6".4, which is greater than the maximum range of 6".0 for the elongation determinations. However, the major portion of the range in the Polaris determinations is produced by two determinations by the same observer. None of the elongation observations were made by this observer, and these two determinations were not made during the period of the elongation observations. Even if these two observations are disregarded, there would still be a maximum range of 3".0 in the remaining six determinations. Rejection of the remaining two determinations of the early group would reduce the range to 2".4 among the remaining four determinations. But it is not clear that even the two determinations which stand out should be rejected. Other instances of large discrepancies have been found in past records which make it seem unwise to attribute the present discrepancies to differences in observer alone.

The elongation determinations are more regularly spaced, but even here the judicious rejection of one of the weakest determinations would reduce the 6".0 maximum range to 4".5.

In whatever manner the comparison of the two sets of determinations may be made, it would seem that only tentative conclusions can be drawn. Using all the determinations, the mean values obtained by the two methods are in excellent agreement. Variations from the mean are slightly better for the elongation method. With the rejection of the two Polaris determinations in question, the mean values differ by about one sec, with the maximum range for the elongation determinations perhaps twice that for the Polaris determinations. Also, except for the preparation and use of an observing list, the field procedures for the two methods are similar.

It appears, then, that the method of observing on non-circumpolar stars near elongation gives azimuths comparable to those obtainable from Polaris. However, additional field work should make more positive conclusions possible, and at the same time yield valuable data on the question of night-error versus personal equations in observing.

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EXPERIMENTAL POSITION DETERMINATION BY PENDULUM ASTROLABE

F. R. Gossett and A. D. Sollins

Abstract--Latitude and longitude obtained using a pendulum astrolabe are compared with those obtained using standard United States Coast and Geodetic Survey methods. The conclusion is that the latitude is comparable in precision, but that the pendulum astrolabe longitude is subject to a systematic error probably due to personal equation.

In the spring of 1945, the United States Coast and Geodetic Survey undertook to obtain a comparison between the position determination made by standard methods of this Bureau and that obtained by pendulum astrolabe. A further purpose was, of course, to familiarize the personnel with the pendulum astrolabe in actual field operation.

Accordingly, a station near Brownsville, Texas, was occupied, and its latitude and longitude determined by observations with the Bamberg broken-telescope transit. The latitude was determined by the Horrebow-Talcott method on four different nights using a total of 34 star pairs, each pair consisting of a north and south star with approximately the same zenith distance.

The longitude was determined by meridian transits on four different nights, each determination consisting of 12 or 13 stars. The impersonal transit micrometer was used together with chronographic registration and radio time control.

The astrolabe position was then obtained by two different observers on four different nights yielding nine separate determinations, with approximately 20 stars per determination. Although the pendulum astrolabe is by now well-known, the following points representing somewhat divergent practice might be noted. The passage of a star across each of five cross hairs was chronographically recorded by means of a hand electric key. A special audio-filter designed by H. G. Dorsey and T. J. Hickley of the Coast Survey permitted an almost continuous recording of WWV time signals upon the chronographic record of star breaks.

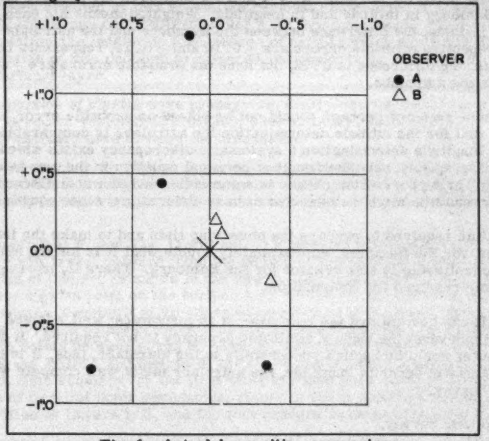

Fig. 1--Astrolabe position comparison

The office computations of the Bamberg results require no comment. For the astrolabe, however, the following points seem important. The necessary zenith distance computations were made for the mean of the five passage times, a procedure which, for stars within 30° of the meridian, necessitated a significant "curvature" correction to their computed zenith distances. Some trials of the method of graphical adjustment were made, and although for a well-distributed set of stars the method proved successful, it was felt that in this case, certainly, a least-squares adjustment was warranted.

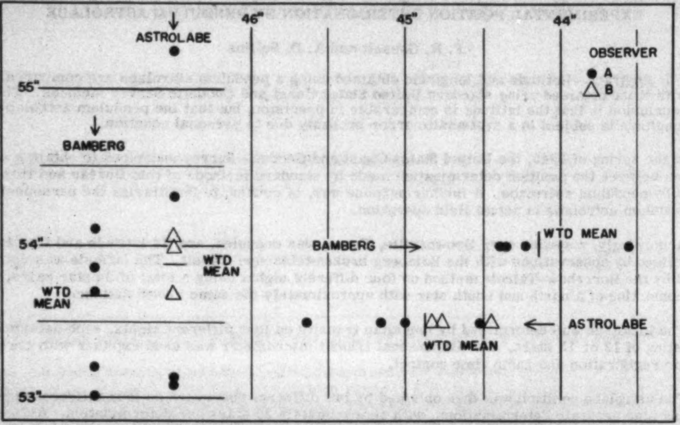

Fig. 2--Comparison of the astrolabe and the Bamberg

The actual comparison of results is indicated by Figures 1 and 2. Figure 1 illustrates the spread in position amongst the astrolabe determinations themselves. The center of the plot represents the weighted mean for the astrolabe. Figure 2 compares the relative spread between the astrolabe and the Bamberg in latitude and in longitude. Weighted means for each instrument are shown by bars. In latitude, the difference between the Bamberg and the astrolabe is 0″.20, which, inasmuch as the respective probable errors are ± 0″.10 and ± 0″.19, represents reasonable agreement. For longitude, the difference is 0″.72, but here the probable errors are ± 0″.14 for the Bamberg and ± 0″.10 for the astrolabe.

Even though undue reliance perhaps should not be placed on probable error, it would appear from these results that for the latitude determination the astrolabe is comparable with the Bamberg; while for the longitude determination a systematic discrepancy exists which is of the size to be expected if the discrepancy were the result of personal equation in the eye-hand reaction in astrolabe observing. In support of this, there is some indication of a real discrepancy between the two astrolabe observers who might be expected to have different personal equations.

The length of time required to prepare the observing lists and to make the latitude and longitude observations is, for the Bamberg, approximately double what it is for the astrolabe. The time required for instrument setup is also greater for the Bamberg. There is, however, very little difference in the time required for computation.

In conclusion, it can be said that the astrolabe is an instrument well adapted to rapid astronomical determinations when the highest attainable accuracy is not required. If the principle of the transit micrometer could be applied successfully to the astrolabe, thus, it is hoped, largely eliminating the systematic error in longitude, the astrolabe might well compete with the Bamberg in the work of this Survey.

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THE VELOCITY OF P IN THE GRANITIC LAYER

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(Paper Number 94 published under the auspices of the Committee on Experimental Geology and Geophysics and the Division of Geological Sciences at Harvard University)

Abstract--Determinations of the velocity of P_1, the direct longitudinal wave through the outermost or granitic layer, have been made by a number of investigators from studies of earthquake records and from timed artificial explosions. In general, the velocity of P_1 has been reported as about 5.5 km/sec from the former and six km/sec from the latter. Gutenberg recently discussed this difference to explain his belief that explosion waves do not give the correct picture.

Gutenberg's suggestions are analyzed, and the entire problem is reviewed in the light of new evidence that personal factors of interpretation have been leading to divergence of results which is more apparent than real.

It is concluded that Gutenberg's P_y, for which velocities have been found between 5.92 and 6.14 km/sec, actually meets the criteria for P_1 and is the phase observed from 0-110 km as the first arrival on explosion records. Such an interpretation fuses earthquake studies and explosion results into a strong unified body of data establishing the velocity of P_1 as in the neighborhood of six km/sec.

Since the first studies of instrumental records of a European earthquake of October 8, 1909 [see "References" at end of paper, MOHOROVICIC, 1910], seismologists have been accumulating elastic wave data bearing on the structure of the surface layers of the Earth. These data have naturally been varied in quality, owing to diversities among station instruments, with those of recent years reflecting marked advances in recording technique. Most notable of these was the introduction of modern short-period galvanometric seismographs and the general use of radio for precise time control.

Results have been affected by this as well as regional differences of structure. Recent reports by HODGSON [1942] and GUTENBERG [1943 a, b], however, made it clear that purely personal factors of interpretation are leading to divergences of results which are more apparent than real. The present discussion of this problem is referred particularly to P-waves in the so-called "granitic" or outermost layer.

Theory--The portion of elastic wave propagation theory bearing on this problem has been set forth many times in recent years [GUTENBERG, 1943 a; LEET, 1938, etc.], but a brief review of certain features is included here to unify the discussion.

The scale of the problem is such as to permit neglecting the Earth's curvature. For purposes of illustration, let us consider a structure consisting of Layers I, II, and III of thicknesses 15 km, 20 km, and undefined, in which longitudinal waves travel with velocities of 6, 7, and 8 km/sec respectively.

An impulse applied at F (see Fig. 1) will set up a complex disturbance in the Earth. The front of this disturbance will travel outward from the source at the velocity of the longitudinal wave. Its position at intervals of one sec is shown in the figure. The travel history of a portion of this wave front which reaches a given point on the surface may be traced by constructing a ray from that point back to the source, keeping it at all times perpendicular to the wave fronts. Results indicate that the first wave to reach points between F and A has traveled along the Earth's surface. The first wave to reach points between A and B, however, has traveled part of its course along or near the top of Layer II (as FCDE), and beyond B, the top of Layer III (as FGHJKL). A graph (see Fig. 1) of distance against time required for the first wave to reach each distance forms three lines. In the assumed case of parallel layer boundaries, slopes of these lines are measures respectively of longitudinal velocities in Layers I, II, and III, with changes in slope occurring at A and B.

Point A is reached simultaneously by the part of the wave which traveled only in medium I and the one generated at the I-II interface. It is a point on a plane represented by the locus CA. Point B, in similar manner, is reached simultaneously by the wave which travels via Layer II, that is, FCMB, and that generated at the II-III interface. It is a point on the locus HMB. Wave-front

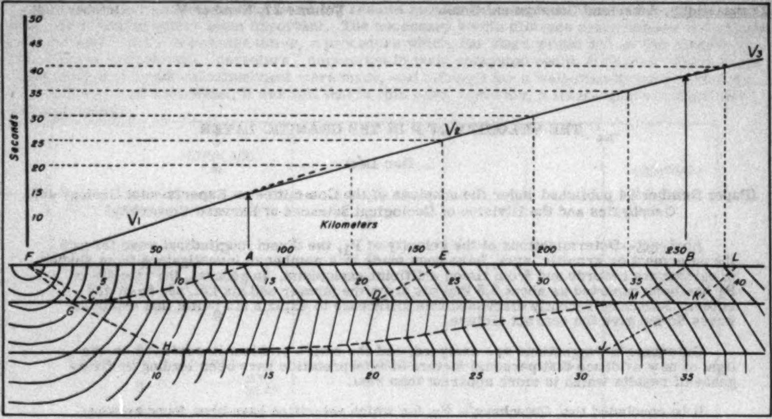

Fig. 1--Wave front diagram and travel-time graph for V_1 = 6 km/sec, V_2 = 7 km/sec, V_3 = 8 km/sec, h_1 = 15 km, and h_2 = 10 km

diagrams of this general sort have been used for some time in seismology [LEET, 1938; SIEBERG, 1923; THORNBURGH, 1930].

Figure 1 describes the history of only the front of the disturbance. Physically, of course, the direct Layer I P-wave, P_1, continues beyond A. At distances greater than FA, it simply arrives after the first wave. In fact, for a certain computable distance short of A the Layer II P-wave, P_2, arrives second and sometimes can be recognized on records. Similar relationships hold for P_2 and P_3 around B.

Owing to the simplicity of its travel history, P_1 suffers less attenuation than P_2 and P_3. It is, accordingly, the most prominent of the three phases on the seismogram. When it is a later arrival, it is normally also the first of a series of relatively large amplitude events representing a variety of combinations of internally reflected first layer longitudinal waves.

These characteristics are among the standard criteria for the recognition of P_1. GUTENBERG [1943 b], for example, states, "At epicentral distances less than about 90 km, the seismograms in California begin with $\overline{P}$, the wave which has traveled solely in the granitic and sedimentary layers. At somewhat greater epicentral distances this phase is usually outstanding because of its rather large amplitude; at distances of a few hundred km, its amplitude decreases, and beyond 600 km it is only rarely identified beyond doubt." The illustration to which this quotation refers shows very prominent $\overline{P}$ phases at 550 km and 570 km, so the cut-off leading to rarity of identification beyond 600 km is either very sharp or open to question, but in general this statement summarizes the case on the basis of observations to date.

If the source is in Layer II, or deeper, the geometry of travel paths would not be expected to permit the existence of a P_1 wave. All energy reaching the surface would traverse Layer I at an angle, as in Figure 1, for the first energy beyond A. At the same time, geometry is not always the controlling factor, and the equivalent of a secondary source at the base of Layer I, from which P waves would radiate, is not excluded if the source is near enough to that base or actually terminates at it.

A special situation is introduced if Layer I transmits waves with a higher velocity than Layer II. The effects of this situation depend directly upon the ratio of the thickness of this high-velocity Layer I to wave length and to distance from the source. There are two general conditions for a surface source, such as a dynamite blast: (a) If the high-speed Layer I is underlain by a structure which includes a Layer II of speed lower than I, and Layer III with speed higher than Layer I, and if Layer I is more than about one-half wave length in thickness, a travel-time graph would not show any first-arrival line for Layer II. Solution of such a case has been discussed by SLICHTER

[1932]; and (b) if, however, with the same velocity conditions, Layer I is relatively thin, it will transmit recordable energy for only a short distance and will not serve as a velocity shield beyond that. This has been established experimentally.

Velocity of P_1 (formerly $\bar{P}$ or P_g)--When waves from natural earthquakes are used, the velocity of this phase cannot be determined accurately within the distance range where it is the first arrival. For the first few km from the epicenter, effects of focal depth and mechanism are unknowns very difficult to evaluate accurately. GUTENBERG [1943 b] eliminates observations at less than 60 km. P_1 ceases to be the first arrival beyond about 90 km in California. The range between 60 km and 90 km is insufficient for satisfactory control in determining the velocity of P_1.

As a result, values for the velocity of P_1 based on earthquake studies have come from arrival times at distances where P_1 was not the first phase. It is now clear that investigators have not always applied the same criteria to the identification of this phase.

The use of artificial explosions offers attractive possibilities, particularly in studies of surface layering. From an exactly located surface source, waves can be initiated at an accurately known time. Investigations using artificial explosions have been made over a period of years in such widely scattered areas as northern Germany, New England, and Southern California.

The velocity of P_1 determined by timed artificial explosions has consistently ranged around six km/sec in contrast to values around 5.5 km/sec determined from studies of earthquakes by certain investigators. In New England [LEET, 1941], the P_1 curve from explosions (velocity 6.13 km/sec) has been extended to about 950 km by readings on an earthquake phase which conforms to Gutenberg's criteria. In one instance in California, waves from timed blasts at Colton, recorded at Pasadena, showed velocities of about six km/sec while Pasadena records of earthquakes at Colton were interpreted by GUTENBERG [1943 a] showing $\bar{P}$ waves with a velocity of 5.59 ± 0.1 km/sec.

GUTENBERG [1943 a] took cognizance of this basic discrepancy between results of the two methods of determining the velocity of P_1 in the following words:

"The use of artificial explosions for investigation of layers in the Earth's crust has the advantage that the exact location and depth of the source and, frequently, the origin time are known. On the other hand, the waves through the deeper layers arrive rather late, the distance Δ' is greater than in earthquakes, and relatively large energies are needed to record impulses b or c over a distance interval great enough to find the velocities in deeper layers. Moreover, the wave velocities in ancient sediments and various types of igneous and metamorphic rocks near the surface may exceed the value of 5.6 km/sec which is usually found in the underlying layer a. Thus, in Ordovician sediments at a depth of 1200 m, velocities near 6.1 km/sec have been observed, and values up to seven km/sec in other ancient sediments; six km/sec or more have also been found in some gneisses, quartzites, dolomites, rock salts, and in many basic and ultrabasic rocks. In all instances where an extensive layer of rocks with velocities exceeding 5.6 km/sec lies above granite (with a velocity of 5.6 km/sec or less), no travel-time curve indicating the granitic layer can be expected, if the source of the waves is in the upper high-velocity layer. Consequently, if a velocity of about six km/sec is found for the direct waves in artificial explosions, as in northern Germany, New England, and Southern California, this may belong to one of the rocks just mentioned even though no specific rock with such a high velocity has been identified. It is not possible to conclude in such instances that the layer with a velocity of 5.6 km/sec is absent. In blasts in Southern California waves traveling near the surface with velocities of about six km/sec have been observed in some areas of about 5.5 km/sec, or both, in others. Especially, about six km/sec have been found between Colton and Pasadena in several recent blasts by C. F. Richter. In this same area, no waves traveling near the surface with six km/sec have been detected in earthquake records, but the velocity of $\bar{P}$ was 5.59 km/sec with a probable error not exceeding 0.1 km/sec in many shocks. The epicenter of one earthquake was only a few km from the source of blasting near Colton. The earthquake waves passing through such high velocity surface layers would arrive a few tenths of a second earlier than usual. These and other differences due to local conditions can be detected only by using a large body of highly accurate data.

"In the other areas with observations of high velocities near the surface, no earthquake data are available. The best observed shocks in New England, the New Hampshire shocks of December 1940, unfortunately do not contribute to the solution, as the nearest stations were too distant to furnish positive evidence for or against the existence of a layer with a velocity of 5.6 km/sec in that region, and, furthermore, these shocks probably originated in one of the intermediate layers; in this case, no travel-time curve corresponding to the velocity in the upper layer exists. The

lowest velocity found by Leet and Linehan for longitudinal waves in these shocks was 6.44 km/sec. Farther to the north, Hodgson obtained the usual velocity of about 5.5 km/sec for longitudinal waves in the uppermost layer in a preliminary investigation of rockbursts in Lake Shore Mines, Kirkland Lake, Ontario, recorded at Ottawa, Canada."

Gutenberg thus offers the suggestion that artificial explosions generate waves which by some selective process carry appreciable energy to distances of 250 km or more through a high velocity surface formation which is too thin to influence earthquake waves measurably, "even though no specific rock with such a high velocity has been identified."

This explanation encounters serious difficulties from some of the observed facts. For one thing, direct P waves from explosions have been recorded with wave lengths of from three to six km. Such waves are not going to carry appreciable energy through relatively thin near-surface sedimentary formations, regardless of velocity conditions. For another, the similarity of results in Germany, New England, and Southern California under greatly varied geological conditions practically eliminates special local conditions as important factors.

Gutenberg adds a further question mark to the explosion results in New England by stating that "Farther to the north, Hodgson obtained the usual velocity of about 5.5 km/sec for longitudinal waves in the uppermost layer in a preliminary investigation of rock bursts in Lake Shore Mines, Kirkland Lake, Ontario, recorded at Ottawa, Canada." This refers to the report by E. A. HODGSON [1942]. In it, Hodgson is clearly reporting as his P_1, referred to by Gutenberg as "longitudinal waves in the uppermost layer," a phase not meeting the criteria of Gutenberg himself or of any other investigators of this problem, and all readings for time of arrival tabulated under P_1 are bracketed as unreliable. Recently, JOHN H. HODGSON [1946] has extended the work described in the preliminary report quoted by Gutenberg. He found a velocity of 6.15 km/sec for P_1.

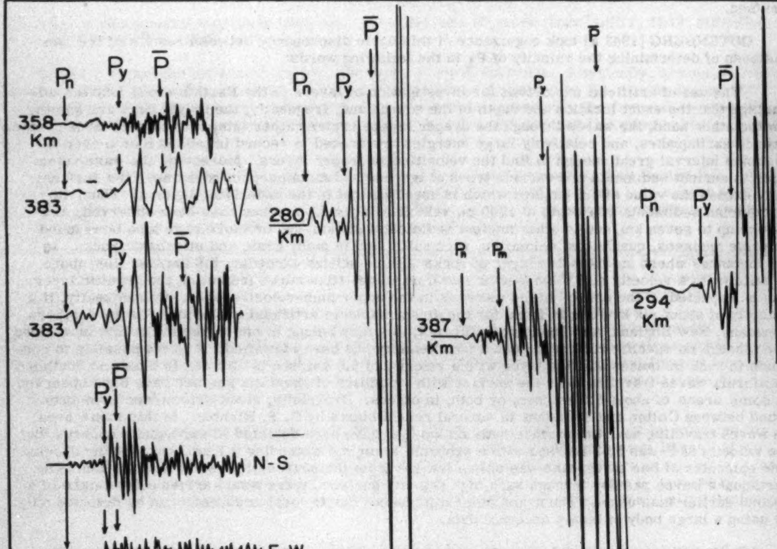

Fig. 2--Characteristic seismograms showing Gutenberg's P_y and $\bar{P}$ [in part after Plate I, GUTENBERG, 1943 a]

From an examination of records recently published to illustrate the picking of various phases, there now seems to be considerable doubt as to whether there is, after all, a basic disagreement among results from earthquakes and from explosions used to determine the velocity of P_1. GUTENBERG [1943 b] reports as a phase called P_y an outstanding phase for which velocities have been found between 5.92 and 6.14 km/sec. Some of the records showing this phase, and the one called $\bar{P}$, are copied in Figure 2. These show P_y to be a phase which meets the criteria for P_1 very well indeed. The fact that a phase of the same velocity can be carried back to the origin by explosion experiments which record it as the first arrival over about 110 km looks like a strong argument for regarding it as the basic direct longitudinal phase in the granitic layer, P_1. Such an interpretation fuses earthquake studies and the explosion results into a strong unified body of data establishing the velocity of P_1 as in the neighborhood of six km/sec.

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RESPONSE OF ELECTRONIC EARTHQUAKE RECORDER

F. Keller

Abstract--Preliminary tests made to determine the response characteristics of an electronic earthquake recorder are described. Tests were conducted with a Wenner and a special seismometer as well as with a Neumann-LaBarre vibration meter. Simultaneous recordings on both smoked paper and photographic paper, which were made on the same drum and from the same seismometer mirror, are shown. The electronic recorder appears to respond satisfactorily to earthquake waves of from one sec to 30 sec or longer in period.

In the amateur seismographic station that has been in continuous operation at New Kensington, Pennsylvania, for the past seven years, an electronic recorder [see "References" at end of paper, KELLER, 1942, 1944 a, and 1944 b] is used. This recorder was designed to respond to seismic waves, and makes a visible trace on a smoked chart or an ink record. It has registered in a very satisfactory manner most of the near and distant earthquakes that have occurred in this period. The United States Coast and Geodetic Survey have followed the development of this recorder and have made it possible to conduct some preliminary tests to compare the results of this type of recording with those obtained by photographic recording. For these tests, the United States Coast and Geodetic Survey furnished a Wenner seismometer and galvanometer, Neumann-LaBarre vibration meter, a photographic recorder, and a Seth Thomas clock with an invar pendulum.

The general arrangement of the apparatus in use at the New Kensington station is illustrated diagrammatically by Figure 1. A specially built seismometer consisting of a small horizontal pendulum with a moving coil is used. The output of the seismometer coil is connected to a Leeds and Northrup Type P galvanometer which is operated at a period of ten sec. The usual shunt arrangement is employed to control the damping. A beam of light of uniform intensity from a closely-regulated current source is reflected from the galvanometer mirror onto a photo-cell pick-up of an electronic amplifier which was designed to give satisfactory response to the long-period waves associated with earthquakes. The output from the amplifier is used to actuate an electrical recorder which in reality is a large galvanometer that has two opposing coils which constitute the plate loads in the push-pull stage of the amplifier.

When the light spot on the photo cell remains stationary, the currents in the two coils are equal and opposite and no deflection of the writing arm occurs. When the light spot moves, however, and illuminates a smaller or larger area of the photocell cathode, the resulting currents in the two coils are 180 degrees out of phase, but the torques are in-phase and the writing arm will deflect in relation to the rotation of the galvanometer mirror. Originally, the writing arm carried a fine-pointed stylus for tracing a record on a smoked-paper chart, but this stylus has now been replaced with a capillary-type pen which will make an ink record.

The character of the response obtained with the electronic recorder when a Wenner seismometer and galvanometer were used to actuate the recorder is illustrated by Figures 2 to 4, inclusive. Figure 2 shows a decay curve for the Wenner galvanometer and illustrates the recording of harmonic motion with a 22-second period. In actual operation, good response has been obtained for earthquake waves with a period of about 30 sec. In Figure 3 is shown a decay curve for the Wenner seismometer and galvanometer combination without any damping. The Wenner seismometer was operated for about six months, and good records were obtained of the earthquakes that occurred in this interval. The Wenner seismometer and electronic recorder combination gave a somewhat higher magnification than was desired, and unusually large amplitudes were obtained for the waves from even moderate earthquakes. It was necessary, therefore, to reduce the distance from the galvanometer mirror to the photo cell to about ten inches in order to keep the traces on the chart. The general response to earthquake waves is indicated by Figure 4, which shows portions from the record obtained on April 15, 1945, of an earthquake that occurred east of Kamchatka, a distance of 7750 km. At the time the Wenner seismometer was in use, a photographic recorder was not available, and therefore it was not possible to obtain a direct comparison of electronic and photographic methods of recording.

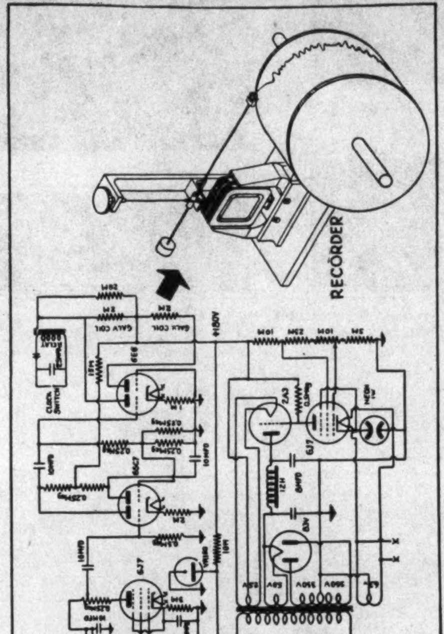
LAMP
MIRROR–GALVANOMETER
SEISMOMETER
RECORDER
AUTOMATIC VOLTAGE REGULATOR
LINE
110V AC
6J7
6SC7
6E6
2A3
6J7
NEON
CLOCK SWITCH
RELAY
GALV COIL
GALV COIL
+150V
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Fig. 1--General arrangement of the apparatus in use at the New Kensington station

Fig. 2--Decay curve of Wenner galvanometer (period 22 sec)

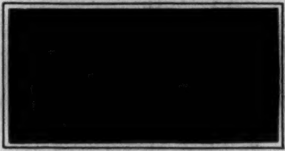

Fig. 3--Decay curve of Wenner seismometer and galvanometer without any damping (period 9.3 sec)

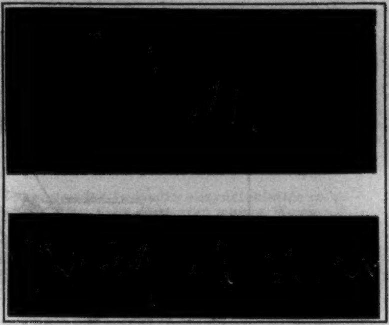

Fig. 4--Curve from records of earthquake on April 15, 1945 (7750 km) made with Wenner seismometer and the electronic recorder

Later, similar tests were made with a Neumann-LaBarre vibration meter [NEUMANN and McCOMB, 1944] and the electronic recorder. At this time, a standard photographic recorder was supplied by the United States Coast and Geodetic Survey with the vibration meter. The equipment was set up in such a manner that simultaneous recording was obtained from the same seismometer mirror and on the same drum.

At first, some difficulty was encountered in obtaining dual recording, as the photographic paper was too sensitive to permit the use of sufficient illumination for the photo cell. A satisfactory solution was obtained by using a dark red filter on the photo-cell lamp. Fortunately, the photo cell responded better to red light than to white light, and the red light did not affect the photographic paper. The response to artificially produced vibrations obtained with the Neumann-LaBarre vibration meter by simultaneous recording is shown by Figure 5. For these tests, the vibration meter was operated at a period of about three sec, employing the large mass fairly close to the hinge and a low magnification spindle. The vibration meter had a 100-cm focusing mirror, and the photographic recorder was operated at this distance. Because of the high magnification obtained with the electronic recorder, the distance from the mirror to the photo cell was 30 cm. Even at this distance, somewhat higher magnification was obtained on the record made with the electronic recording as compared with the photographic recording.

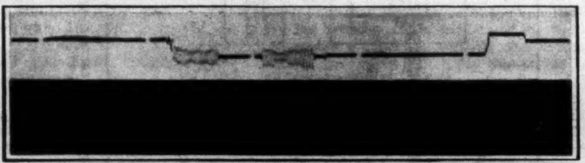

Fig. 5--Response tests with a Neumann-LaBarre vibration meter. These simultaneous recordings were made photographically and electronically from the same vibration meter and on the same recorder drum

From Figure 5, it is apparent that the response of the electronic recorder compares fairly well with that obtained by the photographic method. The electronic recorder will respond satisfactorily to vibrations of one-second period or longer but not to vibrations of shorter period. This is because of the moving system of the electrical recorder having a resonate period between one and two sec. To obtain good response to waves of shorter period, it is necessary to have the resonate period of the recording galvanometer shorter than that of the shortest waves being recorded. This can be done by changing the suspension of the recorder. In operation, the Neumann-LaBarre was very sensitive to tilt, and the zero would shift considerably as is evident from the record. This shifting caused the light spot to go off the photo cell at times, making it necessary to

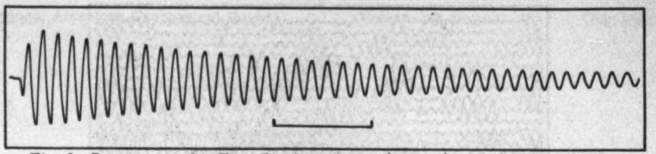

Fig. 6--Decay curve for Type P galvanometer (ten sec) made with electronic-recorder using a capillary pen

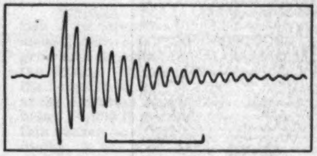

Fig. 7--Decay curve for New Kensington seismometer Type P galvanometer combination without any damping

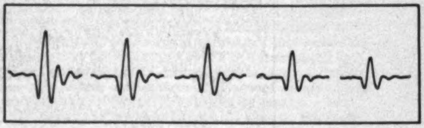

Fig. 8--Damping tests with New Kensington seismometer using various shunt resistances

move the light or the recorder to keep the spot on the photo cell. This condition did not exist with seismometers employing galvanometers.

After the tests were made with the Wenner seismometer and the Neumann-LaBarre vibration meter, the stylus used for making the trace on a smoked chart was replaced with a capillary-type pen with a large reservoir to make ink records. The capillary pen operates with no more friction than the stylus and provides a very excellent and readable record. The pen has been in operation for almost a year and no difficulty has been encountered from clogging. The appearance of the type of records obtained with this pen is illustrated by Figures 6 to 10 inclusive. Figures 6 to 9 show decay curves for the Type P galvanometer and for the New Kensington seismometer system without any damping and the results of damping tests with this combination. A typical ink record made with the New Kensington seismometer system is shown in Figure 9, and the response of this system to moderately heavy microseisms is illustrated by Figure 10.

From these very preliminary tests, it appears that the electronic recorder is capable of responding satisfactorily to earthquake waves of periods of from one sec to 30 sec or longer. Furthermore, with this system it is possible to obtain good visible recording of earth motion at the time it is actually occurring. Electronic recorders of this type are believed to have some distinct advantages that should make them of interest to seismologists.

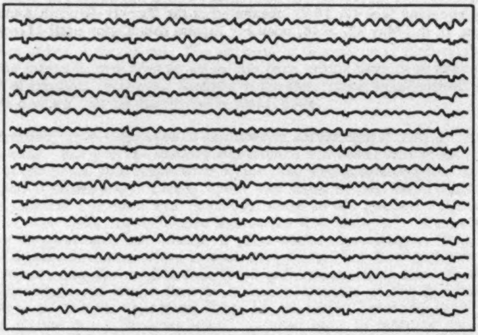

Fig. 9--Typical ink record made with electronic-recorder employing a capillary pen with New Kensington seismometer

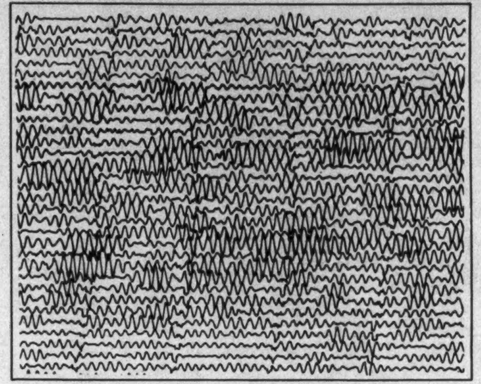

Fig. 10--Typical response of New Kensington seismometer-galvanometer combination and the electronic-recorder to moderately heavy microseisms

Acknowledgments--The author is indebted to O. W. Swainson, E. B. Roberts, H. E. McComb, F. Neumann, and R. E. Gebhart of the United States Coast and Geodetic Survey for their continued interest and cooperation and for the loan of the equipment that was used.

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ON THE MOVEMENT OF TROPICAL CYCLONES

R. H. Simpson

Abstract--The approach of a tropical cyclone is usually accompanied by intensification of circulation aloft in the broad currents on its poleward side. Anticyclogenesis usually occurs downstream from the cyclone, the so-called steering wedge tending to grow and extend westward, which tends to perpetuate the normal westward movement of the storm. The results of this study indicate that the steering level is determined by the height to which the storm's vortical circulation extends, being located approximately at the elevation where closed isobars over the storm disappear. This level ranges from below 10,000 ft to above 50,000 ft and may vary more than 10,000 ft in 24 hours. For this reason no single level can be used to determine the steering of the storm from day to day. It has been found, however, that changes occurring in the flow patterns of the 20,000-foot, or 500-mb, chart are excellent indices to critical changes in movement.

A new tool for forecasting direction of movement for tropical cyclones has recently been developed which is apparently more valuable and effective than steering-level analyses. By using charts of the difference in height between the 700 mb and 500 mb levels (mean virtual temperature charts), or of the weight in millibars of the layer from 10,000 to 20,000 ft, it has been found that a tongue of warmer, lighter air is associated with the moving storm. This tongue is oriented with its major axis parallel to the movement of the cyclone. An excellent lag correlation exists, such that the orientation of the tongue at any instant usually indicates the direction of cyclone movement for the ensuing 24-hour period.

Forecasting the movement of tropical cyclones has long been considered more an art than a science. The success of the hurricane forecaster has been dependent, until recently, upon his ability to apply wisdom gained of long experience to reports from widely spaced observation stations, in order to anticipate changes in direction of cyclone movement. He has had to estimate individually the numerous factors influencing the movement of a storm from the small network of surface reports available and integrate them into a forecast. Such procedure was sufficiently subjective in nature to allow considerable range of probable error. The policy usually adopted in issuing advisories of tropical storms has been to track the storm as accurately as possible, warning the regions in its path which, within the probable range of error, may be affected by its future movement.

The expansion of observational networks during the recent war years has allowed a clearer view of developments in the upper air which accompany the formation and approach of a tropical cyclone. It has provided the forecaster with more exact means of determining the future course of the storm and has opened a new field of research on the nature of forces or "controls" which govern the movement of the phenomenon. The purpose of this paper is to describe some of the factors of prognostic interest, provided by upper air data, which have been used successfully to forecast movement of tropical cyclones. A study of the theoretical implications of these factors is as yet incomplete and will not be discussed in detail here.

The tropical cyclone, when compared to cyclones of extratropical origin, is a relatively small atmospheric eddy. Early in the century experience had shown that these cyclones tend to move downstream in the broad flow patterns in which they are imbedded [see "References" at end of paper, BOWIE and WEIGHTMAN, 1916]. Over two decades ago MITCHELL [1924] suggested the likelihood that tropical cyclones are "carried along in the general drift of the atmosphere at the higher levels, say from three to five km above the surface." Exploration of these early concepts was delayed until the advent of pilot balloon soundings. With expanding networks of this new upper-air information it was soon found that flow patterns or streamlines constructed from winds near the 10,000-foot level and extrapolated into the storm area frequently revealed the pattern of broad flow most representative of the direction of movement of the cyclone. This suggested, therefore, that the so-called "steering level" for tropical cyclones was near 10,000 ft. ("Steering level" is used here to indicate that elevation at which the flow patterns in the region of a tropical "low" are parallel to the direction of movement of the "low.") When radiosonde data became available, it was believed by some that by using both wind and pressure data, accurate extrapolation of flow patterns at this elevation could be accomplished for tropical regions south of the United States, thus simplifying the task of hurricane forecasting. With further expansion of pibal networks, occasional penetrations to the 10,000-foot level were made in regions under the influence of tropical cyclone circulation, and it was found that the cyclone circulation was still pronounced at this level. It became clear that in order to obtain the steering flow, the circulation of the storm would have to be extracted from the broad flow patterns at this level, using as reference those winds downstream and outside the circulatory influence of the storm [DUNN, 1944].

Not until the advent of rawin soundings was it discovered that the intense circulation of the tropical cyclone extended frequently into the middle and upper troposphere, occasionally above 50,000 ft. Careful analysis of successive levels above 10,000 ft up to the tropopause during the life cycles of numerous tropical cyclones in the Atlantic and Caribbean areas, for which expanded networks of radiosonde and rawin observations were available, has revealed certain characteristics of cyclone movement which previously were obscure or unknown. These are discussed individually below.

The tropical cyclone and anticyclogenesis--The development and movement of the tropical cyclone is associated with intensification of circulation aloft in the broad currents of air on its poleward side. This is more prominently displayed in the flow patterns near 20,000 ft than at lower levels. While this acceleration is most marked in the easterlies, there seems to be good correlation between the approach of a deepening tropical cyclone and the speeding up of mid-latitude westerlies to the north and west. The pressure gradient, therefore, increases both on the north and south sides of the steering wedge of high pressure. This acceleration manifests itself through upper-air anticyclogenesis in the subtropical wedge of high pressure, which not only grows but is extended or advected westward. The extension of the wedge westward is frequently of such magnitude that initially strong polar troughs extending to very low latitudes west of the cyclone are filled. In such instances the west winds at low levels favorable for recurvature of the cyclone are replaced by easterlies, allowing the storm to continue an initial westward movement.

It seems probable that the circulation of the tropical cyclone exerts an anticyclogenetic influence upon the subtropical steering wedge, an action which tends to perpetuate the movement of the cyclone westward. Examples of these effects are illustrated in Figures 1-6. Consider the storm of August 17-22, 1942, Figures 1-3. In an incipient state at 23^h on August 16, the storm was surrounded by weak circulation patterns at 20,000 ft. In Figure 2, 24 hours later, the storm had advanced into the central Gulf of Mexico, and the circulation as far north as Canada had increased markedly. The 488-millibar isobar, outlining the wedge of high pressure, had expanded and advanced westward. Late on August 18 (Fig. 3) the wedge had extended as far as New Mexico and had strengthened materially over Texas. The northward movement of the storm had disappeared and it had started moving westward. In Figures 4-6 the effect of anticyclogenesis, occurring downstream from a tropical cyclone, upon an initially deep polar trough is illustrated in the 20,000-foot charts of the disturbance of October 10-12, 1942. On October 10 (Fig. 4) the disturbance was entering its recurvature cycle, while a very deep polar trough approached from the west, carrying a closed circulation at 20,000 ft over Georgia and Alabama. On the following day (Fig. 5) the protrusion westward of a narrow wedge of high pressure north of the cyclone indicated the possibility that further movement of the cyclone northward might be blocked, while the southern portion of the polar trough became separated from the principal stream of westerlies farther north. In addition, the lower portion of the polar trough filled. This trend was verified on the succeeding map (Fig. 6), where it is apparent that the blocking of the wedge was complete. The storm had moved inland as it was deflected southwestward. The filling of the old polar trough was virtually complete at this time.

In connection with the October storm it is well to point out that this disturbance, while maintaining a pronounced and broad circulation aloft, was not a severe storm, and the circulation at the surface was less extensive than that aloft. The highest surface winds observed did not exceed gale force.

Regardless of the factors giving rise to the anticyclogenesis which accompanies the development and movement of a tropical cyclone, the forecaster is confronted with the expediency of recognizing and evaluating at least two conditions which may be regarded as prerequisite to recurvature of such storms: (1) At the latitude of the cyclone, the base of mid-latitude westerlies must be initially as low as the steering level over the region into which the cyclone is moving. ("Steering level" in this instance refers to that level at which the general flow pattern adjacent to the tropical cyclone is oriented parallel to the future path of the cyclone. This concept of steering

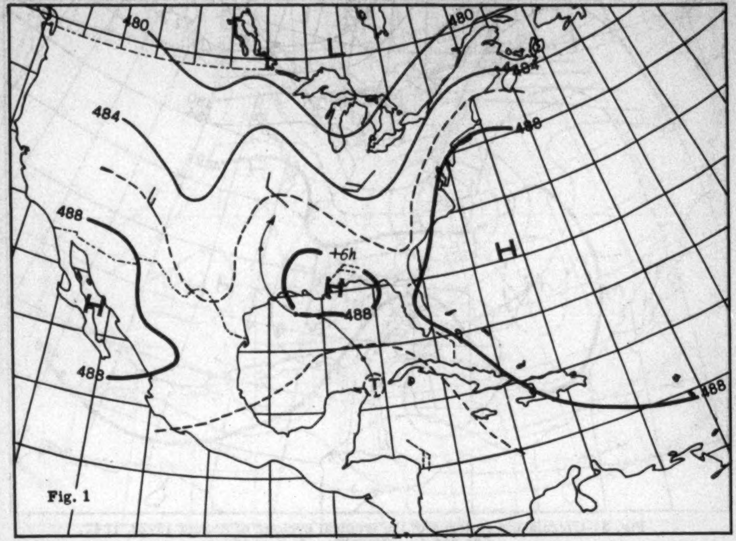
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Fig. 1

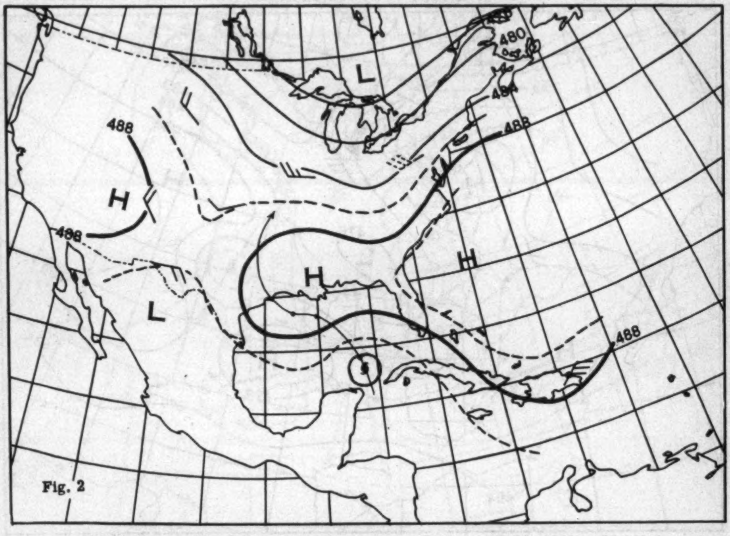
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Fig. 2

Circulation patterns of the tropical cyclone of August 17-22, 1942 at 20,000 ft: Fig. 1, August 16 at 23h00m; Fig. 2, August 17 at 23h00m

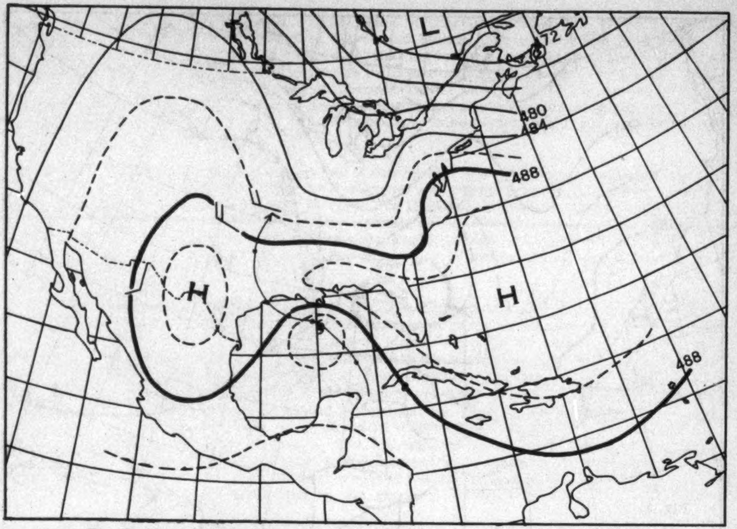
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Fig. 3--Circulation patterns of the tropical cyclone of August 17-22, 1942, at 20,000 ft at 23^{h}00^{m} on August 18

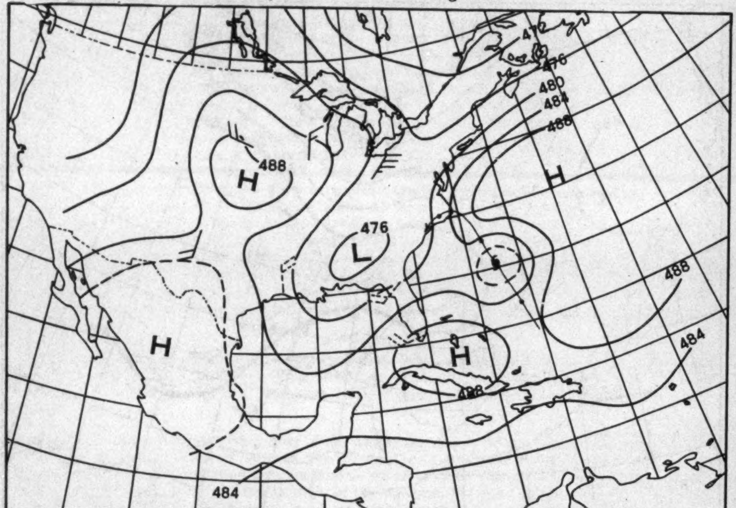
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Fig. 4--Circulation patterns of the tropical cyclone of October 10-12, 1942, at 20,000 ft on October 10 at 23^{h}00^{m}

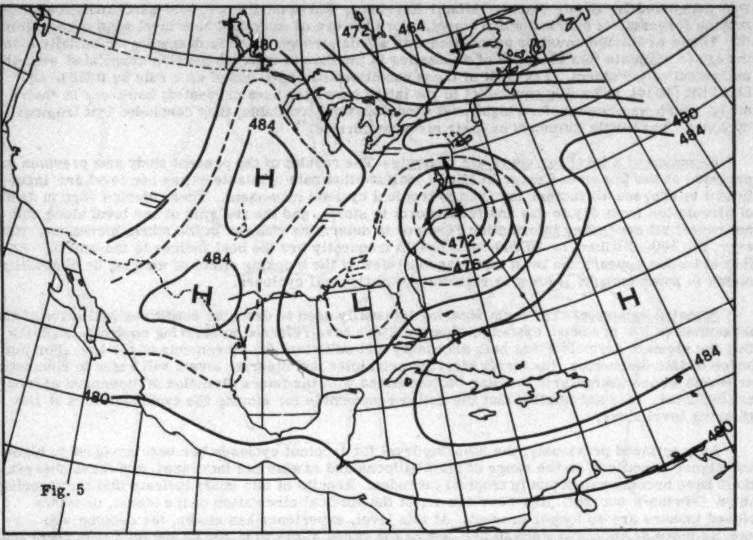
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Fig. 5

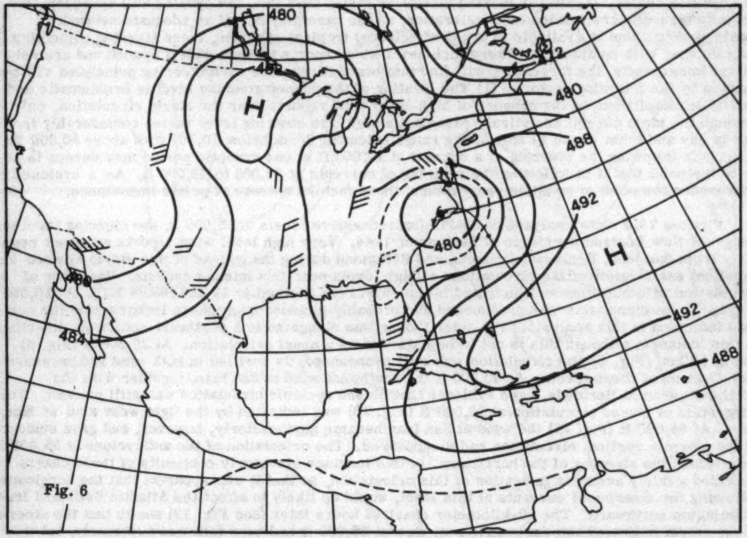
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Fig. 6

Circulation patterns of the tropical cyclone of October 10-12, 1942 at 20,000 ft:
Fig. 5, October 11 at 23h00m; Fig. 6, October 12 at 11h00m

was suggested by Grady Norton, Miami Hurricane Forecast Center, and used analytically in making forecasts of hurricane movement before the era of extensive high level wind observations.) (2) These westerlies must be associated with a polar trough which is deepening or initially strong enough to maintain this low base of westerlies in the face of anticyclogenesis associated with the movement of the storm. The first of these conditions has been stated as a rule by RIEHL and SHAFER [1944], and rules equivalent to the latter have also been presented; however, in their study, which was made before high level wind data were available, they concluded that tropical cyclones "have little influence on their steering current."

Selection of a level for upper air analysis--The results of the present study and previous experience at the Forecast Center in Miami indicate that data available at any one level are insufficient to express all factors involved in tropical cyclone movement. These storms vary in depth of circulation from day to day and from storm to storm, and the analysis of one level alone will not reveal all necessary information required to determine changes in the storm movement. However, the 500-millibar, or 20,000-foot, charts frequently are the best indices to movement. At this elevation appears the most advantageous view of the blocking effect of wedges, or of developments in polar troughs leading to recurvature of tropical cyclones.

Steering principle--The term steering is usually used to describe conditions indicative of the movement of low pressure systems. Some writers have referred to steering controls, implying that the element described was both necessary and sufficient for movements of the low. For purposes of this discussion, the terms steering principles and steering levels will refer to elements or levels whose characteristics may be correlated with the future direction of movement of tropical cyclones. It is not implied that the action responsible for moving the cyclone occurs at the steering level alone.

As mentioned previously, the steering level for tropical cyclones has been assigned to higher and higher elevations as the range of pilot balloons and rawins has increased, and these observations have become numerous in tropical latitudes. Results of this study indicate that the steering level (Norton's concept) lies near the top of the vortical circulation of the storm, or where closed isobars are no longer present. At this level, experience has shown, the cyclone will usually move at approximately 80 per cent of the speed of the wind 200 to 300 mi downstream from the cyclone center. If initially moving slower or faster than this, the cyclone will approach this velocity through acceleration or deceleration, as the case may be. If an adequate network of rawin observations is available in areas affected by tropical cyclones, these steering principles may be used with confidence. Where high-level wind reports become widely spaced and are collected infrequently, the forecaster will find that his ability to use such steering principles will be limited by the following factors: (1) The location of the proper steering level is problematic and can be accomplished, in the absence of high-level wind reports near the storm circulation, only through the most careful analytical reasoning; and (2) the steering level varies considerably from day to day and from storm to storm, the range extending from below 10,000 ft to above 50,000 ft. A cyclone following the steering of a current at 15,000 ft at one synoptic period may deepen in 24 hr to the point that it is following the steering of currents at 30,000 to 40,000 ft. As a cyclone approaches the point of possible recurvature, these factors become of prime importance.

Figures 7-12 show analyses of charts for successive levels to 55,000 ft, the steering level for the great New England hurricane of September 1944. Very high level wind reports received regularly from San Juan, Bermuda, Orlando, and Richmond during the course of this storm allowed an excellent examination of the circulations at high levels near this intense cyclone. Variation of circulation with elevation is illustrated in the charts for September 11 at $11^{h}00^{m}$ EST. At 10,000 ft (Fig. 7) the circulation was pronounced and probably included many more isobars near the center than indicated in this analysis. The outer isobar was elongated in a northeast-southwest direction in this instance, although this is not to be regarded as a usual orientation. At 20,000 ft (Fig. 8) and at 10 km (Fig. 9) the circulation was still pronounced, as verified in both wind and pressure distributions at these levels. At 40,000 ft the southwest wind at San Juan, together with the northwest wind at Bermuda, gave evidence that closed cyclonic circulation was still present. The suggestion of closed circulation at 50,000 ft (Fig. 10) was indicated by the light west wind at San Juan. At 55,000 ft (Fig. 11) the wind at San Juan became northeasterly, however, and gave evidences of the storm's vortical circulation had disappeared. The orientation of the anticyclone at 55,000 ft determined the steering of the hurricane. In this instance six-hourly continuity of these charts provided a fairly accurate indication of this orientation, so that it was apparent that the hurricane, following the steering of currents at this level, would be likely to affect the Atlantic Seaboard from Wilmington northward. The 10-kilometer chart 48 hours later (see Fig. 12) shows that the steering of the storm indicated two days earlier by flow at 55,000 ft had been followed accurately, but that the storm circulation had then fallen below 10 km, which was the steering level at this time. For-

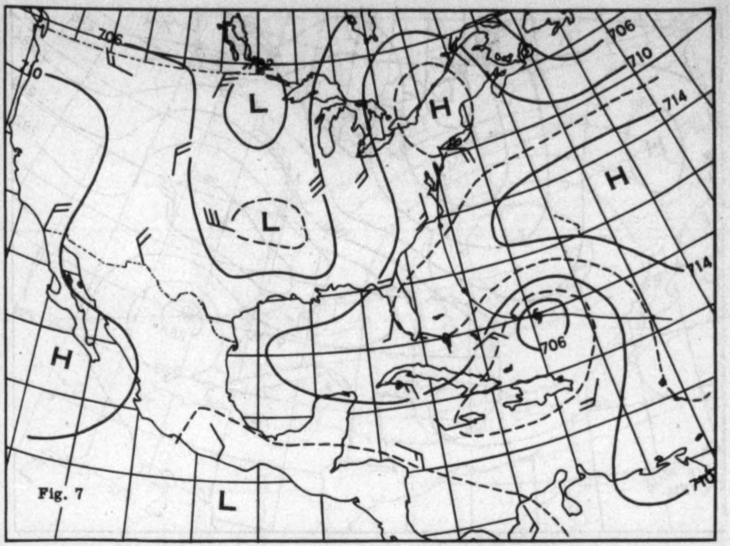
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Fig. 7

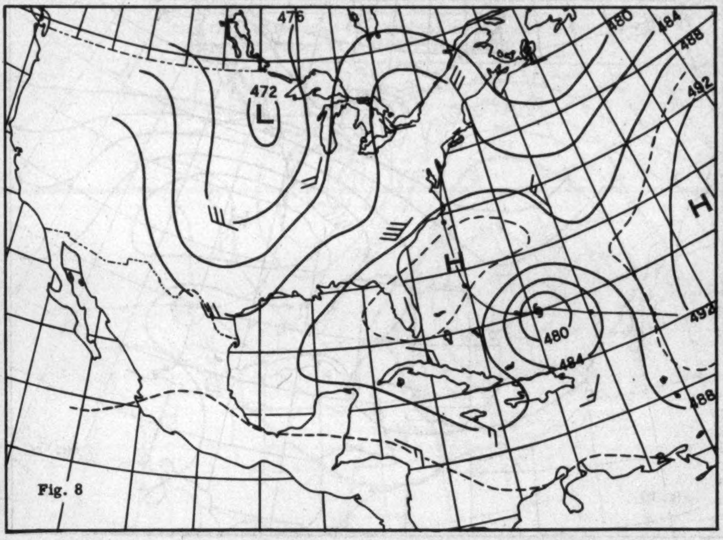
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Fig. 8

Analysis charts of the great New England hurricane of September 1944 at $11^{h}00^{m}$ on September 11: Fig. 7, 10,000 ft; Fig. 8, 20,000 ft

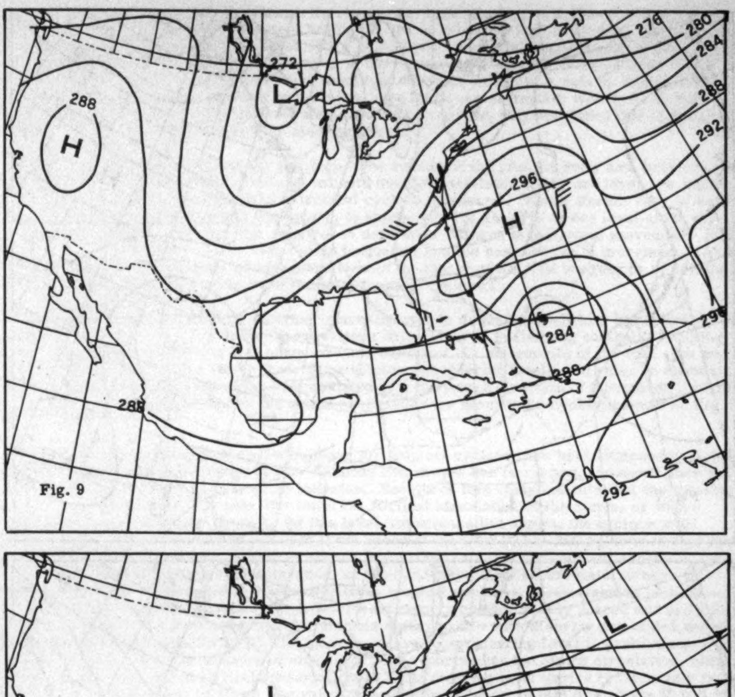
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Fig. 9
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Fig. 10

Analysis charts of the great New England hurricane of September 1944 at $11^{h}00^{m}$ on September 11; Fig. 9, 35,000 ft; Fig. 10, 50,000 ft

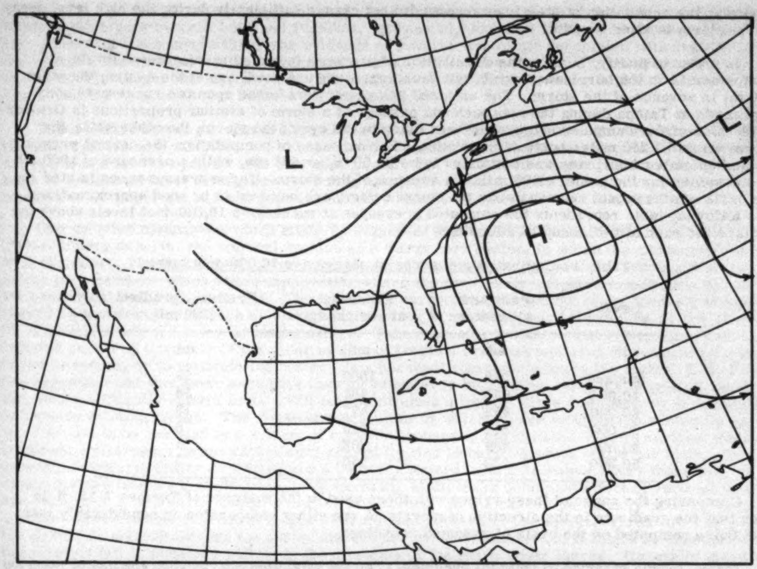

Fig. 11--Analysis chart of the great New England hurricane of September 1944 on September 11 at $11^{h}00^{m}$ at 55,000 ft

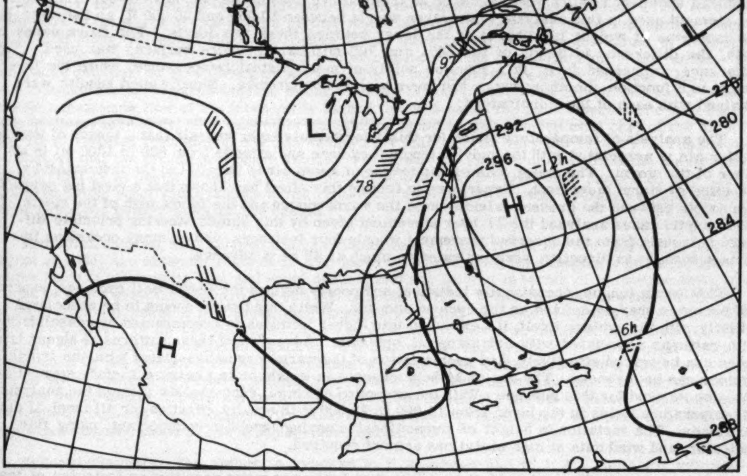
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Fig. 12--Analysis chart of the great New England hurricane of September 1944 on September 13 at $11^{h}00^{m}$ at 30,000 ft, 10 km pressures tunately, the orientation of steering currents did not change sufficiently during the high level decay of the storm to alter its path.

In order to justify, in part, the distribution of pressure indicated at successive levels on September 11 in the hurricane vortex, two soundings were assumed, one at the center, the other 200 mi in advance of the storm. The assumed soundings were based upon two successive soundings made at Tampa during the approach and passage of a storm of similar proportions in October 1944. One of the Tampa soundings had been made in the eye of the storm, the other while the storm was still 200 miles south of the station. For purposes of computation, the central pressure of the September hurricane was estimated to be 28.00 in, or 948 mb, while a pressure of 1000 mb was assumed for the position 200 miles in advance of the storm. These pressures, estimated on the basis of all reports received near the storm center, are believed to be good approximations. The following table represents the computed pressures at successive 10,000-foot levels above the surface for each of two assumed soundings.

Table 1--Computed pressures at successive 10,000-foot levels

Level	Pressure at center	Pressure at periphery	Pressure gradient (200 mi)
ft	mb	mb	mb
Surface	948	1000	52
10,000	663	701	38
20,000	458	477	19
30,000	311	319	8
40,000	204	208	4
50,000	128	130	2

Comparing the range of these values with those used in the analyses of Figures 7-12, it is seen that the gradients in the direction of movement are either comparable or considerably less than those computed on the basis of assumed soundings.

Warm-tongue steering of tropical cyclones--The uncertainties surrounding the use of steering principles described in the section on steering principles led to a search for a more objective tool for forecasting movement of tropical cyclones. Such a tool has recently been developed and has produced excellent results when tested on 25 tropical cyclones of the period 1941-45. The principal element used in this analysis is the layer weight between 10,000 and 20,000 ft, as indicated in the isopleths of weight (millibars) of the layer between these two levels. For those cases in 1945, the difference in height of the 500- and 700-millibar pressure surfaces was used. This difference, expressed in ft, is a function solely of mean virtual temperature, while the layer weight is a function of both pressure and mean virtual temperature. Equally good results were obtained with each of these indicators.

The analysis of temperature fields for this intermediate layer reveals that a tongue of warmer, lighter air is associated with the moving tropical cyclone and extends from 800 to 1200 mi in advance of the storm. The major axis of this tongue of warm air is parallel to the instantaneous direction of storm movement. Experience in testing this effect has shown that a good lag correlation exists between the present orientation of the warm tongue and the future path of the storm. In 139 synoptic cases analyzed the 24-hour movement given by this simple steering principle differed seriously from the observed movement in only four instances, and on many occasions important changes in direction were indicated as much as 48 hr in advance.

This warm tongue, occasionally indistinct and poorly defined for very small cyclones, expands and becomes sharply defined as the cyclone deepens. While this tongue seems to be associated initially with the cyclone itself, its extension into higher latitudes is accompanied by consolidation with patterns associated with extratropical systems. Advection of these patterns at higher latitudes can be traced effectively, and reorientation of the warm tongue associated with the tropical cyclone can be foreseen. The use of 24-hour changes in weight or in pressure surface separation can also be used for this purpose. With the exception of small, very shallow storms the analysis of temperature fields in the layer from 10,000 to 20,000 ft is equally effective for all tropical disturbances. The variation in height of conventional steering levels is unimportant, using this indicator, and wind data at high elevations are not required.

In an attempt to determine whether some other layer was more sensitive an indicator of the warm tongue associated with the tropical cyclone movement, or if a reversal of the effect occurred at any elevation over the cyclone, a similar analysis was made of the mean temperature fields in the layers between 5000 and 10,000 ft, between 20,000 ft and 10 km, and between 10 and 13 km. In each of these layers there was evidence of a warm vein of air associated with regions near and ahead of the cyclone, but the tongues were not as well-defined as in the layer from 10,000 to 20,000 ft. For larger storms, however, the analysis of the layer between 20,000 ft and 10 km was approximately as good as that between 10,000 and 20,000 ft.

Theoretical reasons for this preferred orientation of a tongue of warm air associated with the tropical cyclone are not clear. Perhaps the mechanism by which anticyclogenesis is initiated downstream from the cyclone also accounts in part for this warm-tongue phenomenon, a maximum of horizontal mass divergence occurring along this axis. A study of the nature of this tongue constitutes an important basic research problem which is being initiated at this writing.

One possible mechanism which might be suggested follows DURST and SUTCLIFF [1938]. These writers describe the tropical cyclone as a warm core system in which the winds decrease with elevation. The horizontal convergence of spiralling winds at low levels is accompanied by rising parcels of air which attain an elevation where the pressure gradient is insufficient to balance the centrifugal and coriolis forces. The spiralling parcels are thrown out of the isobaric channels toward higher pressure at such an elevation, resulting in net divergence (deepening of the storm), or in maintainance of the low pressure center. This reasoning indicates that rising air within an isolated region of warm air of the order of size of tropical cyclones will tend to produce a center of low pressure, or to maintain the center. In a personal communication to the author, J. R. Fulks has suggested that this same reasoning may be extended to include the case of a tongue of warm air, where vertically upward motion will tend to produce a trough of low pressure, or to maintain an already existing trough. The simplest mechanism by which we can imagine the vertically upward motion to be initiated is a system of cyclonic isobars at the ground or ocean surface where frictional convergence in the cyclonically curved field of isobars requires rising air aloft. In general, therefore, theory would require a tendency toward falling pressure where there are cyclonic surface isobars beneath a tongue of warm air aloft, if the combined effect of vertical motion and sharpness of the warm tongue is sufficiently strong. In the case of an already existing tropical cyclone where the axis of a warm tongue aloft extends outward in one direction from the center of the storm, or extends through the center and is sharper in one direction, it might be expected that the greatest fall in pressure will be in the direction of the sharp warm tongue. Generally speaking (disregarding variations in pressure gradient) the storm must move in the direction of greatest falls in pressure.

If this is the mechanism which accounts for the movement of tropical cyclones in the direction of the axis of the warm tongue aloft, a further implication of the tendency toward maximum divergence aloft along the axis of the warm tongue is that there should also be a maximum of vertical velocity aloft (but below the level of maximum divergence) in the same quadrant of the storm. This is because only part of the divergence aloft results in falling pressure at the surface; a large part must compensate for the convergence which is known to take place at low levels, and there must then be a maximum flow of air from low to higher levels beneath the point where there is a maximum of divergence aloft. The only other possibility would be that a substantial part of the diverging air is supplied from above, and this seems very unlikely. At very low levels it is reasonable to presume that the maximum upward velocity will occur somewhere upwind from the maximum upward velocity at higher levels. CLINE [1926] and McDONALD [1942] have suggested that the maximum piling up of winds occurs in the right front quadrant of tropical cyclones so that at low levels air rises most rapidly in this region.

Examples showing the analysis of mean virtual temperature fields for two storms, in June and August of 1945, are shown in Figures 13-19. Mean virtual temperature isopleths are indicated by broken lines of alternately long and short dashes, and are labeled in terms of the height difference, in tens of ft, between the 700 millibar and 500 millibar levels. Warm tongues are indicated by hatching from northeast to southwest, cool tongues by hatching from northwest to southeast. Solid lines are contours of the 500 mb pressure surface in tens of feet with the first digit omitted; for example, 920 indicates a height of 19,200 ft. The current surface position of the tropical cyclone is indicated by the symbol 🌀 of the International Weather Code, and its track by a continuous thin line on which successive 24-hour positions at $07^{h}30^{m}$ EST have been marked. The correlation between warm-tongue orientation and subsequent storm movement is self-evident. The discrepancy in Figure 15 between warm tongue orientation and cyclone movement after 12 hours is one of four such discrepancies found in 139 synoptic cases examined.

Acknowledgments--The author is indebted to J. Bjerknes and to J. R. Fulks for valuable counsel and helpful suggestions in connection with this research. In addition, he wishes to thank

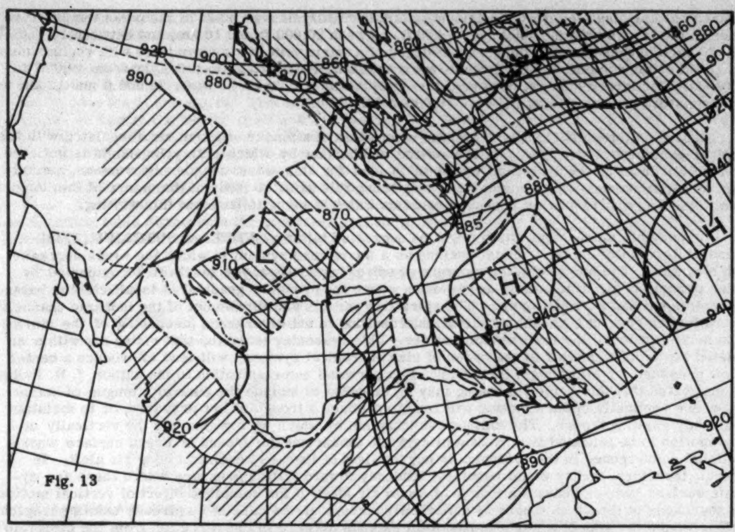
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Fig. 13

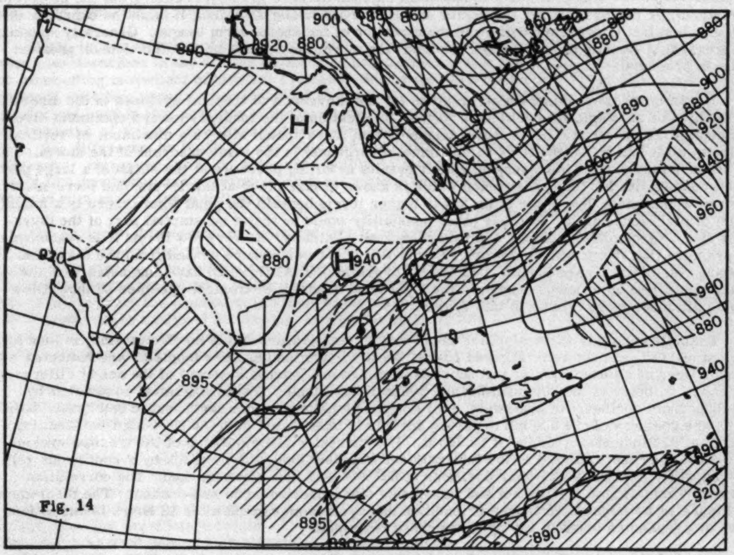
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Fig. 14

Charts of mean temperature fields for storm of June 1945;
Fig. 13, June 21 at 23^h00^m; Fig. 14, June 22 at 23^h00^m

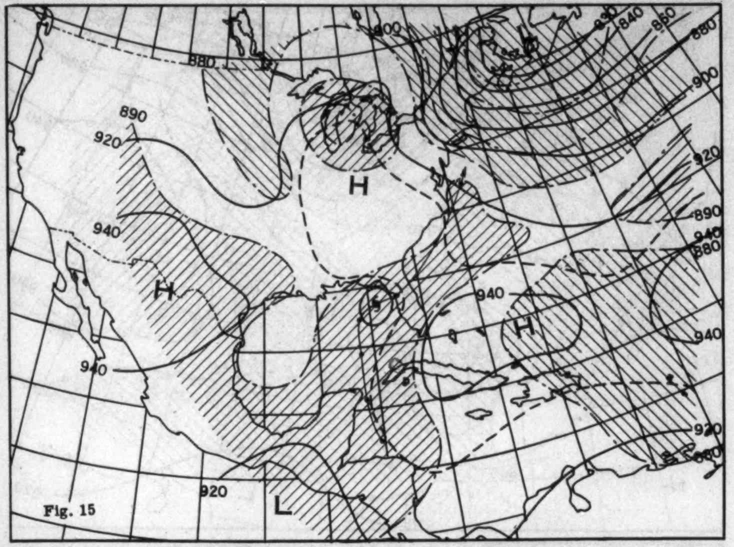
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Fig. 15

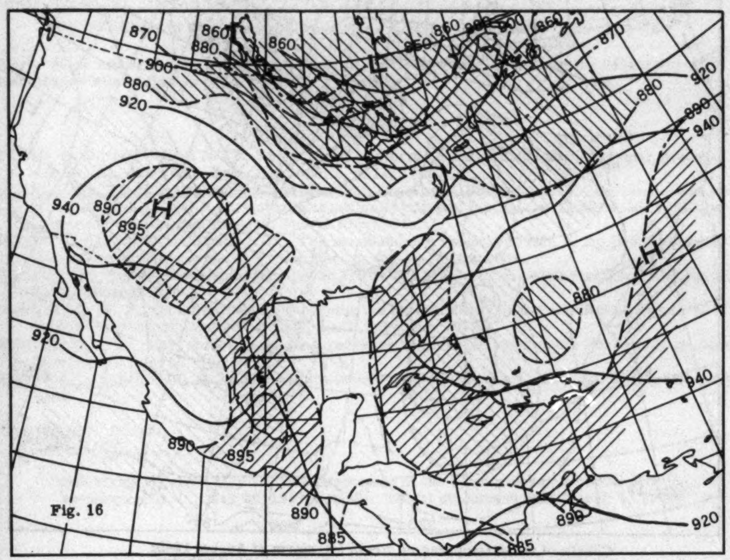
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Fig. 16

Charts of mean temperature fields: Fig. 15, storm of June 22, 1945 at 23^{h}00^{m}; Fig. 16, storm of August 25, 1945 at 23^{h}00^{m}

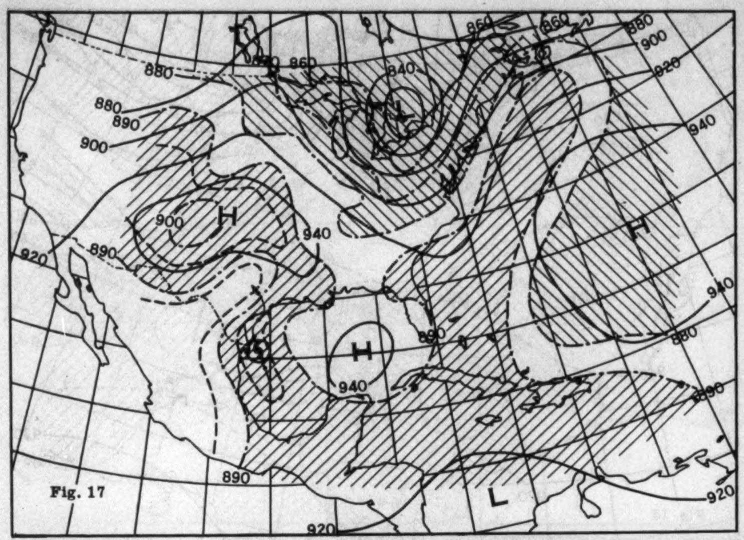
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Fig. 17

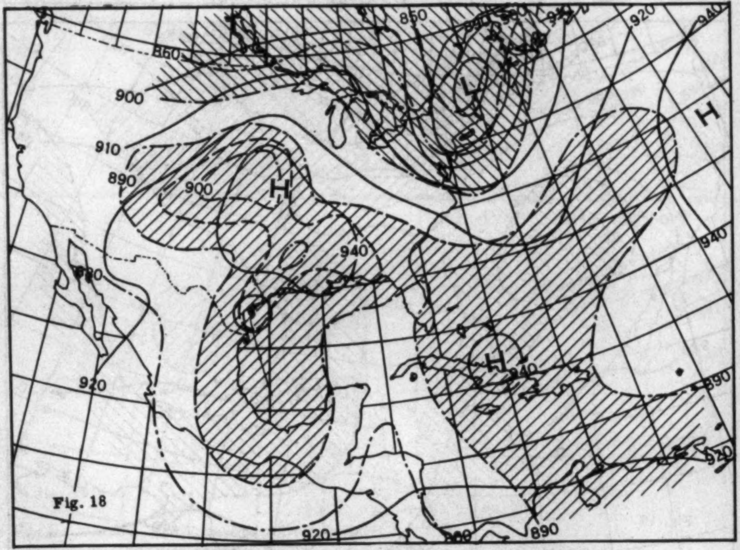
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Fig. 18

Charts of mean temperature fields for storm of August 1945;
Fig. 17, August 25 at 23h00m; Fig. 18, August 26 at 23h00m

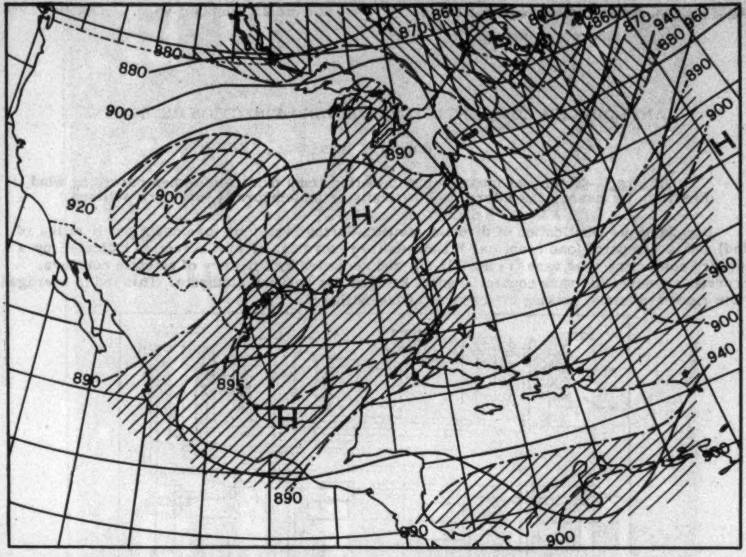

Fig. 19--Chart of mean temperature fields for storm of August 27. 1945 at $11^{h}00^{m}$

Roger Allen and Glenn Brier for their cooperation and active assistance in connection with technical details of this study.

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Transactions, American Geophysical Union   Volume 27, Number V   October 1946

ANTI-DUPLICATION CONTACTORS FOR WIND-DIRECTION RECORDERS

Ronald L. Ives

Abstract--Electrical means for eliminating count duplication when recording wind direction, by means of counters, isokinetically or isotemporally, are here outlined.

Introduction--Duplication of direction counts, during isokinetic (one count per N miles of wind) and isotemporal (one count per N time-units) recordings of wind direction indicated by a standard contacting wind vane (Friez 363-C), and recorded by a battery of electric counters, occurred whenever the vane contact element bridged two position elements. This led to overages in the recorded totals, making the records undependable.

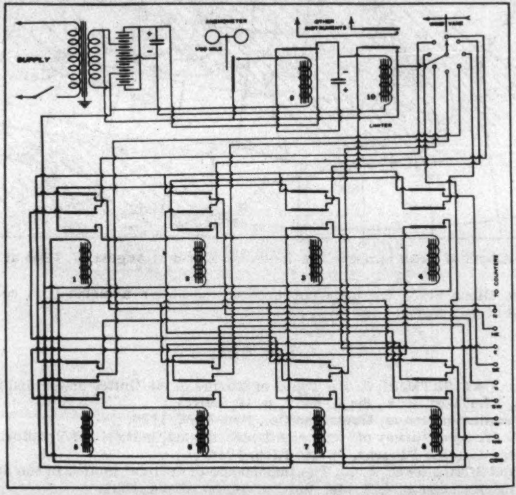

Fig. 1--Circuit diagram of count-duplication eliminator, simplified by omission of pilot lights, fuses, static drains, and auxiliary contacts for operation of other equipment [Relay numbers correspond to direction contacts, increasing clockwise from north (1); relays 9 and 10 are controlled by the anemometer contacts]

Mechanical elimination of this bridging being unfeasible without the introduction of a "dead space" between elements, various electrical duplication eliminators were experimented with, the most successful being here described.

General theory--Duplication of direction counts can be completely eliminated if, when one direction element of the vane is energized, both adjacent elements are temporarily disabled. This can be accomplished mechanically by use of a fragile, "cranky," and rather undependable series of snap contactors, or electrically, by use of a battery of relays. Electrical methods are here preferred, as they use all standard parts, of adequate ruggedness and dependability to insure continuity of record.

Circuits--Circuit of the electrical duplication eliminator is shown in Figure 1. Several rather obvious alternatives, using the same general principles are possible.

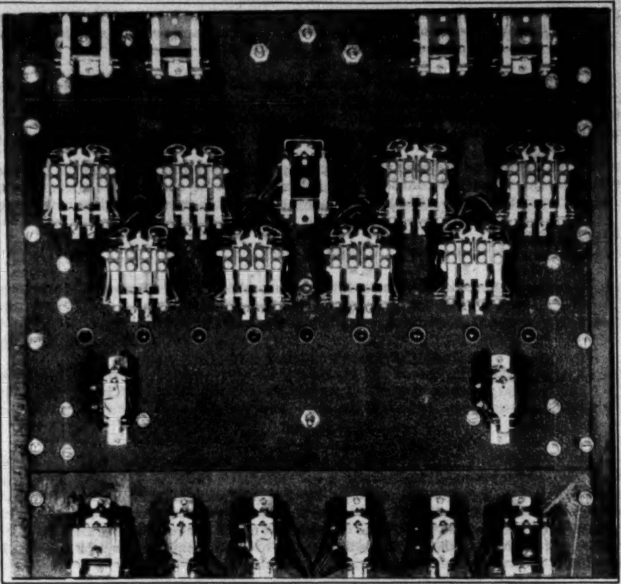

Fig. 2--Appearance of count-duplication eliminator

Operation of this circuit, here shown connected for isokinetic recording (one count per 1/60 mile), is relatively simple. The relay corresponding to any position of the vane pulls down when the contacts for that position close, connecting the corresponding counter, and disabling both adjacent relays. At each interval contact, the counter connected to the "down" relay, and only that counter, counts one.

Specific sequence of operations for one position--SOUTH (vane contactor at bottom of contact circle)--is as follows: Current flows from transformer through vane contacts to center contacts of relay 6, which are closed, as the relay is not energized, then to the lower contacts of relay 4, which are closed, as the relay is not energized, and thence through coil of relay 5 to transformer. This pulls down the armature of relay 5, connecting SOUTH counter in circuit through the top contacts.

Closure of the anemometer contacts actuates the limiter circuit (relays 9, 10, and auxiliaries), which momentarily closes the counter circuit (from transformer through lower contacts of relay 10, through upper contacts of relay 5, to counter), causing the counter to "up one."

If, at any time after the SOUTH relay (5) is pulled down, either adjacent contactor on the vane is closed, no change in the relay positions will occur until the SOUTH circuit is opened, no matter how much bridging takes place. Hence, duplication of counts by bridging is impossible.

Operation for all other vane positions is analogous.

Performance--Performance of this type of count-duplication eliminator is quite satisfactory, provided workmanship is rugged and parts chosen are adequate for the purpose. General appearance of such a duplication eliminator, after slightly more than one year's service, is shown in Figure 2. Relays were mounted on the front panel to permit easy servicing, and vertically to prevent accumulations of dust, which were severe in the local environment.

Maintenance consisted of monthly cleaning of contacts, quarterly overhauling of armature hinges, and semiannual inspection of all components. Life of components exceeded industrial-service ratings by about 50 per cent, despite dust and chemical fumes.

Conclusions--The anti-duplication contactor here described performs as planned, with somewhat better continuity of service than was predicted. Its use, in special meteorological recorders and similar devices, where count duplication due to contact bridging is undesirable is indicated in areas and environments where more elegant mechanical duplication eliminators are unworkable.

[Note: Commenting on the electrical circuit as outlined in the above paper a referee remarks: "The merit of this device is, of course, that the sum of the wind speeds, as indicated by the counters for the various directions, will always equal the total wind passage at the anemometer."--Ed]

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THE MOTION OF TROPICAL CYCLONE PAIRS

B. Haurwitz

Abstract

Whenever two tropical cyclones appear simultaneously in the same region, it is observed that they move around and approach each other in a characteristic fashion. In order to explain this relative motion it is assumed that the cyclones can be approximated by simple vortices. The motion of a vortex pair is studied theoretically, and it is shown that the vortices must rotate around a common center of gravity whose position is determined by the circulation around each vortex. The angular velocity of the axis of the vortex pair is equal to the arithmetic mean of the angular velocities with which the two vortices rotate relative to each other.

The results of the theoretical investigation are applied to the motion of the typhoon pair which appeared in the Western North Pacific in August 1945. All parameters in the expression for the angular velocity can be expressed by observable quantities so that the velocity of rotation can be computed. The agreement with the observed 24-hour displacement is very good.

It is also possible to give a formula for the rate at which the typhoons approach each other. But, because of the sparseness and unreliability of the data, this rate cannot be computed with any accuracy in the present case.

[Note: The complete paper will be published in the Journal of Meteorology.]

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ELIMINATION OF "DISREGARDED FRACTIONS" IN WIND-SPEED TIMING

Ronald L. Ives

Abstract--Methods and equipment for increasing the accuracy of wind-speed measurements, particularly at low speeds, are here outlined.

Introduction

The conventional method of measuring wind speed by counting the total number of closures of the contacts of a 1/60th-mile anemometer during one timed minute, and considering the obtained figure to be the wind speed, is subject to a maximum error of an appreciable portion (often 0.8) of the interval between contact closures.

The absolute magnitude of this error being constant, its relative influence is greatest at low wind speeds. The error may be either plus or minus, and is substantially compensating, but it is undesirable in studies where the accuracy of a relatively few wind-speed measurements is important.

Various methods of eliminating this error were investigated [IVES and KROONA, 1946; IVES, 1945], and most satisfactory general results were obtained when duration of the whole number of intervals between anemometer contact closures just exceeding one minute was used as the computing base. This method retains (approximately) the "one-minute sample" commonly used in meteorology, while eliminating errors due to "disregarded fractions" of speed intervals; requires no new equipment, as used in most weather stations; and may be used in conjunction with automatic timing equipment if desired.

Minimum-error short-term wind-speed measurement

Introduction--Method here outlined requires an ML-80 anemometer or equivalent (equipped with 1/60th-mile contacts), some sort of contact-closure indicator, a stopwatch, and an operator. Obvious modifications of the method here described will adapt it for use with anemometers of other contact ratios, or speeds in terms of other than miles per hour.

Procedure--When all equipment is ready for operation, a speed signal is awaited, and timing is started as soon as it is perceived. The initial speed signal, and all others during one minute, are counted, but timing is continued beyond one minute until one more speed signal, not counted, is received. Timing is then stopped.

Computations--From the procedure outlined above, it should be obvious that the number of contact closures counted is the number of sixtieths of a mile of wind that turned the anemometer during the timed period, which is somewhat greater than one minute in most instances, exact duration being indicated by the reading of the stopwatch.

Wind speed may be determined from the time required for the passage of a single sixtieth of a mile by use of formula (1).

$$S = 60/D \quad \ldots\ldots (1)$$

In which S = wind speed in miles per hour, D = time of passage of one-sixtieth mile of wind in seconds.

Where N intervals are concerned, formula (2) is used.

$$S = 60N/ND \quad \ldots\ldots (2)$$

For convenience, this may be rewritten as in formula (3).

$$S = 60N/T \quad \ldots\ldots (3)$$

In (3) T is the total time in seconds for the passage of N sixtieths of a mile of wind, and is indicated by the stop watch. This computation is ideally suited for slide rule use.

Accuracy--This method of wind-speed timing is subject to the usual instrument errors, but has no inherent observational error of first order. A very small and negligible error is introduced by the non-compensation portions of the observer's reaction time.

When an hour's wind travel is determined by extrapolating from the speed determined by this method, error due solely to extrapolation is very slightly reduced, in some instances, because the timing period is slightly more than the one minute used in several other methods. Some improvement in the overall accuracy of extrapolated values also results from elimination of the "disregarded fractions" previously referred to, but this improvement is usually not great.

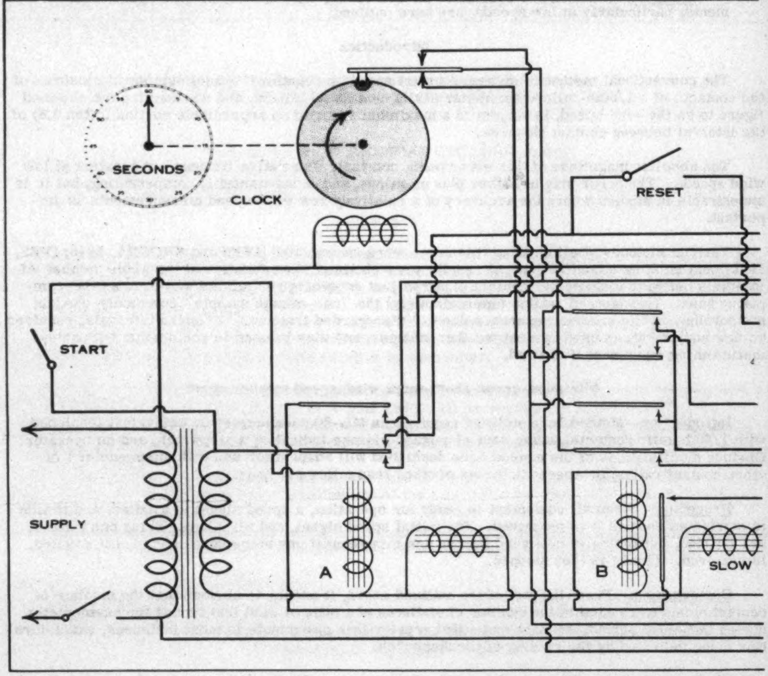


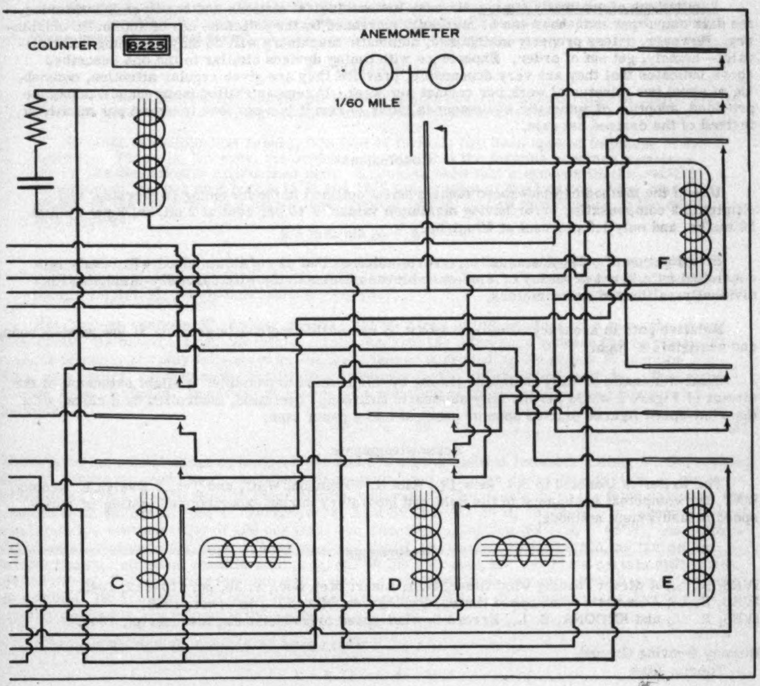
Fig. 1--Wiring diagram of automatic timer for use

Automatic timing device--In some types of work, it is desirable or necessary for the wind-speed timing to be done automatically. This eliminates observer errors (but not instrument-reading blunders or miscomputations), and makes it possible for the observer to be operating other equipment while the wind speed is being timed. An automatic timer supplying the necessary data for wind-speed computation in accord with (3) above can be made by a simple modification of a previously described wind timer [IVES, 1946]. The wiring diagram of this modified timer, which appears more complicated than it is, comprises Figure 1. Operation of this timer, although straightforward, involves a number of steps. When the clock hand is at 60, the counter at zero, and the power on, it is ready for operation.

Momentary closure of the start switch sets the device for operation by pulling down the armature of relay A, which locks in position. This energises the anemometer circuit, so that relay F pulls down at each anemometer contact closure.

At the first anemometer contact closure after setting, relays B and D pull down, lock in position, and disconnect themselves. Relay B energises the clock; relay D connects the counter in circuit, so that it indicates one count immediately, and one count thereafter, for each anemometer contact closure, until disconnected.

Rotation of the clock cam raises the arm of the roller switch controlled by it, so that the lower contact opens, and the upper closes. This energises relay C, which, after taking over the functions of relay B, disconnects itself.



with short-term, minimum-error timing method

The counter continues to accumulate numerical increments of one digit for each anemometer contact closure until the clock completes one revolution (60 seconds). The roller switch then drops into the slot in the clock cam, closing the lower contacts, which in turn close the circuit through the release coil of relay D. This releases the armature of relay D, which disconnects the counter and its own release coil. The clock continues to run.

On the next anemometer contact closure, after the completion of one minute, relays A and C are released, disconnecting their own release coils in the process, and deenergising the clock.

At this time, 60 plus the clock reading is T of (3) and the counter reading is N. These readings are retained by the timer until it is reset, so that computation of the wind speed need not be done immediately. Various indicators or alarms may be connected to the timer so that it will announce completion of measurements.

Before the next operation, the timer is reset, by means of a "run-around" connection, by pressing the reset switch momentarily. This closes relay E, which, through a self-holding connection, maintains the clock-motor connection until the cam reaches the zero position, at which time the roller switch opens its upper contacts, deenergising the relay, and stopping the motor. The counter can be reset manually, or by a solenoid connection (not shown).

Limitations of automatic timing--In busy meteorological stations and research laboratories, the data output per man-hour can be markedly increased by the judicious use of automatic machinery. However, unless properly maintained, automatic machinery will do only one thing automatically--namely, get out of order. Experience with timing devices similar to the one described above indicates that they are very dependable, provided they are given regular attention, consisting of about two minutes of work per contact per week. If regular skilled maintenance cannot be provided, adoption of automatic equipment is likely to result in a net loss in output per man-hour, instead of the desired net gain.

Conclusions

Use of the method of wind-speed measurement outlined in the foregoing paragraphs will eliminate a compensating error having maximum values of 40 per cent at 2 mi/hr, 8 per cent at 10 mi/hr, and only 1.6 per cent at 50 mi/hr.

Investigation of other anemometer errors indicates that use of this method will result in a consistent gain in net accuracy of wind-speed measurements only with carefully-maintained individually-calibrated anemometers.

Relative gain in accuracy of measurement by use of this method is greatest at low wind-speeds, and negligible at high.

Semi-automatic or fully automatic timing by this method is possible: a slight extension of the circuit of Figure 1 would permit fully automatic unattended operation, controlled by a clock, with the wind-speed figures printed upon or punched into a paper tape.

Acknowledgments

The writer is indebted to Sgt. (now Lt.) Rita K. Wilkinson, WAC, and Tec. 3 Evelyn L. Kroona, WAC, for competent assistance in the field and laboratory during experimental testing of wind-speed measurement methods.

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USUAL FORMULAS OF CONTINENTALITY AND THEIR LIMITS OF VALIDITY

V. Conrad

Abstract--Equations given by W. Zenker in the last decade of the Nineteenth Century and later modified by other authors, characterizing the degree of continentality at a given place have the general form:

$$k = mA/\sin\phi + n$$

where k = the continentality coefficient in per cent, A = average annual range of temperature at a given place, ϕ = geographical latitude, and m and n are constants.

In other climatological papers, this type of formula has been applied to places in low latitudes. There is, however, the obvious objection that the formula becomes meaningless if the denominator approaches zero. Examples show that k exceeds its theoretical maximum of 100 per cent within 12°N and 12°S independent of the location of the place; inland, on the coast, or on a small, innertropical island. A new modification of the equation is given:

$$k = mA/\sin(\phi + \phi_o) + n$$

where $m = 1.7$, $n = 14$, and $\phi_o = 10°$. For latitudes greater than 80 degrees it should be assumed, as a sufficient approximation, that $\sin(\phi + \phi_o) = 1$. The new formula, although purely empirical, avoids contradictory results.

For obvious reasons, W. Zenker used the annual range of temperature as a measure of continentality. He based his considerations on the fact that the difference between the warmest and coldest month is not only influenced by the land masses surrounding the region in question but also, as a natural consequence of radiation conditions, by the geographical latitude. Therefore, Zenker used "reduced" temperature ranges as a measure of continentality and proposed the formula:

$$k = 1.2A/\phi - 20 \quad \ldots\ldots\ldots\ldots \quad (1)$$

where A is the annual range of temperature and ϕ the geographical latitude. Later, W. Gorczynski, Osc. V. Johansson, and others modified this formula, in particular by the introduction of $\sin\phi$ instead of ϕ. This modification is theoretically preferable. The constants of the formulas were calculated from empirical limits. Verkhoyansk, East Siberia (67°33'N, 133°24'E), is assumed to be a region with a continentality of 100 per cent, and Thorshavn, Lofoten (62°2'N, 6°44'W), one with a continentality of zero per cent. These bilateral limits, introduced by Johansson, as far as the writer knows, represent considerable progress on the one hand, but introduce certain difficulties on the other. The resulting formula now appears as derived from regions within a narrow range of latitude. Its application to other latitudes is an extrapolation. Nonetheless, the formula is usually applied to any region of the Earth.

The special formula considered here reads:

$$k = 1.7A/\sin\phi - 20.4 \quad \ldots\ldots\ldots\ldots \quad (2)$$

where A and ϕ have the same meaning as in formula (1). The writer twice previously has pointed to the simple fact that this equation loses its meaning if $\phi \doteq 0$ [see "References" at end of paper, CONRAD, 1936, p. 124 and 1944, p. 169].

Although this theoretical objection is simple and obvious, it may be of some interest to consider the results which are derived in practice from the observations made in the interior belt of the tropics [HANN, 1910; KNOCH, 1931]. Seventy-two places within 12°N and 12°S were selected at random.

The results are summarized in Table 1 and Figure 1. The latitudes, ϕ, are averaged, disregarding north or south latitude. Neither table nor figure require much explanation. On the average a place in 0°.9 latitude with an average annual range of 2°.2 C shows a continentality coefficient, k, of 445 per cent, that is, 4-1/2 times as great as Verkhoyansk assumes with full continentality of 100 per cent. This result is independent of the location of the stations whether inland, Table 1--The continentality coefficient k calculated from temperature records in low latitudes

Number of places	Average ϕ	Average k
16	0.9	445
14	2.8	60
11	4.8	32
9	6.8	32
9	8.9	12
13	11.0	10

[a] This column was calculated, as usual in climatology, by averaging the indicated quantities for k for each of the number of places shown in the first column. Calculating the curve of k for the ϕ and A values shown results in a curve similar to that of Figure 1 with the first value equal to 218 instead of 445.

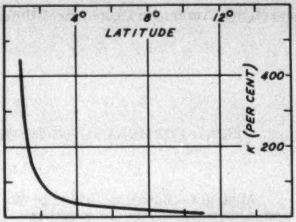

Fig. 1--The behavior of the continentality coefficient k within low latitudes

on the coast, or on an island. In other words, the result does not indicate continentality at all. The influence of latitude in the formula for continentality is so strong that it overwhelms any other factor.

It becomes obvious, however, particularly from Figure 1, that, starting from about 9° latitude, the curve approaches the X-axis more or less asymptotically. Thus, the simple consideration yields validity limits of continentality formulas of the Zenker type. These formulas are not applicable within the belt between 10°N and 10°S, but a very cautious investigator may use them for latitudes upwards from 15° or 20°.

These validity limits suggest a very simple modification of the previously-mentioned formula

$$k = bA/\sin(\phi + \phi_0) - c \quad \ldots\ldots\ldots\ldots \quad (3)$$

The additional angle ϕ_0 eliminates the absurd values obtained for the continentality coefficient, k, within the inner tropic belt. According to the previous result, one could take $\phi_0 = 10°$, while it is perhaps more advantageous to assume the value c = 14, given by Johansson. The formula

$$k = [1.7A/\sin(\phi + 10°)] - 14 \quad \ldots\ldots\ldots\ldots \quad (4)$$

yields for Verkhoyansk about 100 per cent and for Thorshavn about zero per cent and more or less reasonable values for the inner tropics. The disadvantage is that the formula loses its validity at latitudes greater than 80°. However, from the standpoint of descriptive climatology this restriction is not too serious, as it comprises a relatively small area. To my knowledge, only one regular station exists at present in these high latitudes for which an average annual range of temperature is known, Green Harbor, Spitsbergen [WAGNER, 1919, pp. 709-758]. Since this range of temperature is 19°.2 C and the latitude is 78°2'N, a continentality of k = 19 results from the new formula. This is a very plausible value. For latitudes greater than 80° the denominator could be assumed to be unity. If a final equation of the new formula of the Zenker type were adopted, a large number of places in different latitudes and localities of different continentality would have to be considered until convenient values of ϕ_0, b, and c were obtained. Formula (4) is given only as a preliminary suggestion

Finally, one should not lose sight of the fact that the purpose of these formulas is only to represent roughly the effect of continental land masses on the climate of a given place as compared to the climate of the same place on an Earth covered with water (continentality zero per cent). Therefore a formula of the Zenker type which avoids contradictory results would be desirable.

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SIMULTANEOUS COSMIC RAY MEASUREMENTS ON THE EMPIRE STATE BUILDING TOWER AND AT FORDHAM UNIVERSITY

Frank A. Benedetto

Abstract--Mesotron intensities are being simultaneously recorded at Fordham University, 142 ft above sea level, and on the 87th floor level of the Empire State Building (ESB), 1125 ft above sea level. Identical types of cosmic ray telescopes are used at each station, and the aperture of each telescope is such that the sensitive cone is not screened by the tower structure of the ESB. By this method of simultaneous observations, errors due to variations of barometric pressure and atmospheric temperature are largely cancelled, since the final calculations of mesotron intensity for any given period are determined by the ratio of the counting rates of the two telescopes during the same period.

Each telescope is permanently screened against the softer component by 20 cm of lead. For the first series of observations both telescopes were located at Fordham, and alternate runs were made with and without an additional screening of 35.5 gm/cm^2 of lead above the telescope destined to be placed at the ESB; this procedure was repeated after transfer of that telescope to the ESB.

An increase of 3.3 per cent in intensity at the higher station is computed and is interpreted as representing that fraction of mesotrons decaying while traversing the 983 ft difference in elevation between stations. A mean free path of 9.34 km is thus indicated. For mesotrons of $\gamma = 17.5$ the resultant lifetime, τ_0 is 1.8×10^{-6} sec.

Observations are being continued with a view of determining τ_0 through correlation of mesotron variations with variations in altitude of certain pressure levels of the upper atmosphere.

Introduction--The anomalous absorption by air as contrasted with the almost constant mass absorption displayed by solids in the diminution of cosmic ray intensity has been interpreted as due to the instability of the mesotron component of cosmic radiation. An appreciably longer interval of time is required for traversal through a column of air than through a solid absorber of the same number of gm/cm^2. Since the mass absorption relationship is practically a constant for all solids and liquids, it could be expected to hold in the case for gases were it not for the very short lifetime of the mesotron. It has been shown by FERMI that a slight departure from the mass absorption phenomenon can be expected due to the polarization of the dielectric. However, this correction is admitted to be much too slight to explain away the anomalous atmospheric absorption.

Temperature effect--Various methods have been used in attempts at evaluation of the lifetime, τ_0, of the mesotron at rest. The temperature effect, that is, decrease of mesotron intensity with increase of atmospheric temperature, is explained by the vertical shifting of the atmosphere with the consequent vertical displacement of the effective production level for mesotrons. BLACKETT [see "References" at end of paper, 1938], taking $\tau_0 = 2.7 \times 10^{-6}$ sec was able to bring experimental measurements of mesotron variations into agreement with known atmospheric temperature variations through his well-known relation

$$\alpha = -(1/L)(dh/dT) = -(1/N)(dN/dT) \qquad (1)$$

where α = observed temperature coefficient (- .156 per cent/°C, BLACKETT); L = life range of mesotron; and dh/dT = increase in height of mesotron production layer per unit increase of temperature (50M/°C, BLACKETT-HUMPHREYS). The relation between the life range and the rest lifetime is

$$L = c\gamma\tau_0 = (p\tau_0)/m_0; \quad \gamma = p/m_0c \qquad (2)$$

where γ = relativistic increase of mass or momentum.

It is now known that discrepancies in the observed values of the temperature coefficient can be explained in terms of the geometry of the measuring apparatus. In general, a vertical telescope will indicate a higher coefficient than will a non-directional ionization chamber. Typical values of α range from - 0.1 to - 0.2 per cent/°C from ionization chamber measurements [COMPTON and TURNER, 1937], and from - 0.35 to - 0.46 per cent/°C by vertical telescope [BENEDETTO, ALTMANN, and HESS, 1942; DUPERIER, 1944]. Other considerations, such as thickness of absorbing screen and especially the method of measuring temperature variations and estimating the "production level," influence greatly the calculated value of the temperature coefficient. Until recent years the temperature coefficient was calculated from the prevailing temperatures at the level of the cosmic ray observatory. Recent workers have used radiosonde data, and temperatures were averaged either according to a spatial [DUPERIER, 1944] or a mass average [BENEDETTO, ALTMANN, and HESS, 1942; DUPERIER, 1944] up to the altitude of the assumed production level. All in all, the estimation of mesotron lifetime from the temperature coefficient leaves much to be desired, especially in view of our limited knowledge of mesotron production.

Direct methods--Before passing on to the height differential method of evaluation of lifetime, it should be mentioned that a very ingenuous "direct" method of observing mesotron decay has been worked out by RASETTI [1941] and later refined by ROSSI [1943] and collaborators. Essentially, Geiger counters and associated recording circuits are disposed so as to measure the exponentially distributed time lags between the stopping of mesotrons by some absorber and the emission of decay electrons accompanying this process. By this method Nereson and Rossi observed a value $\tau_0 = 2.15 \times 10^{-6}$ sec. Only two or three cloud-chamber photographs are on record as recording the mesotron decay-electron emission phenomenon [WILLIAMS and EVANS, 1940]. Rossi's direct method appears to be the most accurate and flexible in application. It would be extremely interesting to see this circuit applied in the control of a cloud chamber.

Height differential method--Following Rossi's analysis [ROSSI, HILBURY, and HOAG, 1940], the procedure here is essentially the comparison of mesotron intensities at two stations of different altitudes h and h + dh. The difference in altitude between stations, dh, can be expressed in terms of a certain number of gm/cm^2 mass difference, h likewise is expressed in gm/cm^2. Hence the difference in mesotron intensity as measured at that station under (h + dh) gm/cm^2 of air alone and the intensity measured at the higher station, which has an additional solid absorber above it such that $(h + dh)_{air}$ gm/cm^2 = $(h_{air} + dh_{solid})$gm/cm^2 gives the number of mesotrons, dN, that are lost through decay in traversing the air path difference in altitudes.

Letting dz = difference in altitude of the two stations, in cm, and L = life range of mesotron,

$$-(dN/N) = -(dz/L), \text{ or } L = dz/(\log N_1 - \log N_2) = dz/\log(N_1/N_2) \quad \ldots\ldots\ldots (3)$$

Description of apparatus--Two cosmic ray telescopes of rather conventional design are in use for this investigation. Originally [BENEDETTO, ALTMANN, and HESS, 1942] this apparatus was used by the author and his collaborators during some investigation into the temperature effect. The Geiger counters are arranged in trays which in turn are supported by a sturdy steel frame (see Fig. 1). Three trays of counters together with associated amplifiers and power supplies comprise each telescope. To avoid screening by the tower structure of the Empire State Building, only nine of the original sixteen counters are connected in each tray. As these counters overlap to form a continuously sensitive area, the effective width of each tray is the width of five counters placed side by side and is approximately 11 cm. The length of the tubes is 19.3 cm. Distance between top and bottom trays is 62 cm. Screening against the softer component is afforded by 9.5 cm of lead between top and middle tray and by 10.5 cm of lead between the middle and bottom tray in each telescope. Additional screening against possible side showers due to the tower structure of the ESB is afforded by a 10 cm iron screen arranged about the periphery of the lower tray in the ESB telescope. The high potential of - 900 volts for the Geiger counters, and the power for the coincidence circuit amplifiers were obtained from stabilized power packs which were fed by a self-regulating transformer. Voltages were checked daily; no noticeable drift occurred throughout the course of this investigation. Each telescope and associated equipment are housed in insulated and thermostated demountable huts of approximately 6 ft × 5 ft × 5 ft. In the discussion the telescope permanently stationed at Fordham is labeled "lower" while the other telescope, whether in operation at the ESB or at Fordham, is labeled "upper."

Measurements--With both telescopes set up on the roof of the Physics Building at Fordham, 142 ft above sea level, the daily mesotron rates were observed over the period from February 19, 1946, through March 5, 1946, each telescope being screened by the 20 cm of lead as mentioned above. From March 6 through April 3 an additional lead absorber of 35.49 gm/cm^2 was placed above the upper telescope (still at Fordham), and daily rates of each telescope were recorded.

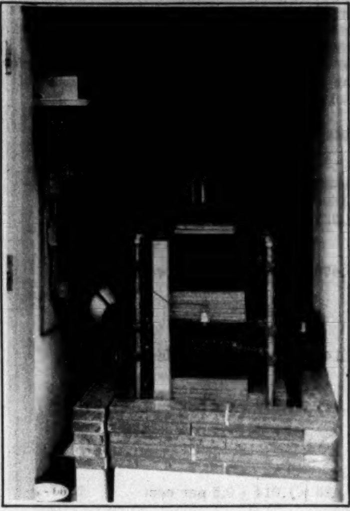

Fig. 1--Upper telescope and housing

This 35.49 cm/cm^2 (34.78 mb) absorber is approximately equal to the average 35 mb difference in pressure between the 87th floor level of the Empire State Building, 1125 ft above sea level, and the Fordham roof, 142 ft above sea level. The additional absorber was then removed for another simultaneous run of five days.

The upper telescope with hut and associated equipment was then moved to the ESB and placed in operation on the northeast corner of the 87th floor level, on the roof of the enclosed portion of the 86th floor observation platform. The axis of each telescope was always set 30° east of north to utilize the largest possible aperture determined by the location at the ESB. Procedure in the ESB observations was similar to that while the telescope was at Fordham. Alternate runs were made with and without the additional lead absorber over a period of 25 days. During the entire course of the experiment readings of each telescope were taken once per day. Data thus accumulated were grouped according to the experimental condition of the upper telescope, and the lumped sums are given in Table 1.

Calculation of results--Since a differential effect of a few per cent can easily be masked by the normal variations caused by barometric, temperature, or magnetic disturbances, it is important to know just what variations are occurring during the period under investigation. For this reason the lower telescope was used as a "control," and all upper telescope results are referred to the lower telescope readings over the corresponding period of observation. Table 2 illustrates how these comparisons are made. As an example, from (I) it is seen that an increase of about 2.6 per cent resulted from shifting the upper telescope to the ESB level. However, (I') shows that over the same periods of observation the mesotron intensity diminished by about 3.5 per cent. Consequently the corrected value for increased rate due to elevation of station is 1.063. This increase of 6.3 per cent is due to the summation of two effects, that is, the less mass, and the shorter path traversed in arriving at the higher location. Correction for the first term is made by measuring the absorption in lead of thickness comparable with the 35 mb difference between the two elevations.

Table 2, (III) and (III') give the ratios used in this determination. It is seen that while the rate decreased about 1.4 per cent due to the extra lead, the control telescope indicated an increase of about 0.6 per cent. Consequently the corrected factor due to mass absorption in lead is 1.020, which in turn must be increased by about one per cent, becoming 1.031, because of the slight departure from a strictly constant mass absorption law. This last one per cent correction is indicated by absorption measurements by ROSSI and collaborators [1940], whose results show a rate ratio of 4.960/4.908 in lead and carbon respectively. We have corrected our absorption in lead to that in carbon, because theory indicates that the mass absorption of carbon and air is the same.

Table 1--Lumped sums of counts for both stations

Minutes	Counts	Rate	Experimental condition
29,890	160,278	5.362	Upper, Fordham, no lead
29,700	162,688	5.478	Lower, Fordham
37,038	190,574	5.145	Upper, Fordham, lead on
37,284	199,130	5.341	Lower, Fordham
18,959	104,294	5.501	Upper, ESB, no lead
18,606	98,339	5.285	Lower, Fordham
14,240	77,268	5.426	Upper, ESB, lead on
14,346	76,273	5.317	Lower, Fordham

Evaluation of mesotron lifetime--The above data can be summarized: Increased rate, referred to unity, because of shorter path and less absorber, 1.063; increased rate, referred to unity, because of less absorber, 1.031; and net increased rate, referred to unity, because of shorter path only, 1.033 ± 0.9 per cent. Consequently, the mean life range as calculated from Equation (3) where dz = 983′ = 0.2996 km is L = 0.2996 km/log 1.033 = 9.23 km. This is in close agreement with the value 9.4 km obtained by ROSSI and collaborators [1940] in their Colorado experiments. Equation (2) gives the relation between L and τ_0. Inserting for γ a value of 17.5, which is the best estimate of the average value for p/m_0c, the value of τ_0 is $\tau_0 = 9.23 \times 10^5$ cm/(17.5 × 3 × 10^{10} cm/sec) = 1.8 × 10^{-6} sec.

Table 2--Ratios of counting rates for both stations

Experimental condition	Rate ratio	Designation
Ratio of upper at ESB to upper while at Fordham, no added lead	5.501/5.362 = 1.026 ± 0.4 per cent	I
Ratio of lower to lower at Fordham during above interval	5.285/5.478 = 0.965 ± 0.4 per cent	I′
Ratio of upper at Fordham, no added lead to same with added 35.5 gm cm^2 lead	5.362/5.145 = 1.042 ± 0.4 per cent	II
Ratio of lower to lower at Fordham during above interval	5.478/5.341 = 1.026 ± 0.4 per cent	II′
Ratio of upper at ESB, no added lead to same with added 35.5 gm/cm^2 lead	5.501/5.426 = 1.014 ± 0.5 per cent	III
Ratio of lower to lower at Fordham during above interval	5.285/5.317 = 0.994 ± 0.5 per cent	III′

Discussion--The method of simultaneous observations of mesotron intensities at stations differing moderately in altitude yet close enough to be influenced equally by the factors that are known to cause fluctuations, such as barometric pressure, atmospheric temperature, and magnetic disturbances, appears to offer decided advantages over methods in which these disturbing factors can not as well be corrected for. The inherent errors of this method are the natural statistical fluctuations common to all random phenomena, which as seen in the previous sections can be brought down to below the limit of accuracy set at present by the lack of precise data on the average momentum spectrum.

This investigation is expected to continue until about June 5, 1946, and accumulated data will be correlated with altitude variations of certain pressure levels of the upper atmosphere as indicated in the radiosonde reports covering this period.

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ON THE IONIZATION PRODUCED BY THE GAMMA RAYS FROM QUINCY GRANITE

Victor Francis Hess

Abstract--With an ionization meter devised by O. H. Gish and the author, experiments were carried out to determine the average ionization produced by the penetrating rays from uranium-radium and thorium products as well as by the gamma rays from potassium contained in a very homogeneous sort of granite quarried at Quincy, Massachusetts. The uranium-radium and thorium content of this sort of granite was determined very carefully by EVANS and GOODMAN in 1941 [see "References" at end of paper]. The potassium content was estimated as three per cent.

The ionization measurements performed in the quarry in August 1945, by the author and F. A. Benedetto, and later experiments carried out with 400 lb of crushed Quincy granite at Fordham University, show that the ionization actually observed above a plane surface of granite amounts to almost 6 I, while the value computed from the known uranium-radium, thorium, and potassium content is only slightly above 2 I. Similar discrepancies were found in the laboratory experiments. These discrepancies cannot be explained by assuming that part of the excess ionization is due to secondary radiation produced by cosmic rays impinging on the surface. It must be concluded either that the reported values for the uranium-radium and thorium content are much too low, which is unlikely, or that a hitherto unknown penetrating radiation is given off by the granite.

Scope of present study and experimental procedure--More than four years ago the author pointed out [1941] that the observed difference in the ionization of hermetically sealed vessels over land and over water cannot be accounted for if one accepts the recently reported low values for the radium-uranium and thorium content found by EVANS and GOODMAN [1941] as representative for the various classes of rocks.

It seemed worth while to investigate this discrepancy. The large variations existing between specimens of the same type of rock taken from different localities makes it hazardous to draw conclusions on the average content of any type of rock and to derive figures for the gamma ray ionization to be expected in individual cases.

Such comparisons are meaningless if they are not made with very homogeneous types of rocks.

Among the numerous rock specimens investigated, Evans and Goodman recommended to the author the Quincy granite, the diabase from the Palisades, New Jersey, and the granites from Fitchburg, Rockport, and Chelmsford, Massachusetts as especially suitable for a quantitative comparison.

I decided to study first the ionization produced by the granite from Quincy, Massachusetts.

The experiments were performed in the quarry of Swingle Company, in Quincy in August 1945, and were continued with a large quantity of crushed granite (400 lb) from the same source at Fordham University.

The ionization apparatus was constructed upon the suggestions of the author and O. H. Gish by the Department of Terrestrial Magnetism, Carnegie Institution of Washington, in 1942 and improved for field experiments in 1943. It is expected that this will be described in detail by O. H. Gish and K. L. Sherman at a later time.

Figure 1 shows the main features of this ionization meter. Three ionization chambers, of 1.6, 4.9, and 13.1 litres volume, respectively, hermetically closed and filled with dry, aged nitrogen at atmospheric pressure can be used alternatively, in connection with a Lindemann electrometer which serves here only as a null instrument. The electrometer housing and the guard-ring systems of the three chambers are kept at 135 volts. Only one of the three chambers is shown in the figure.

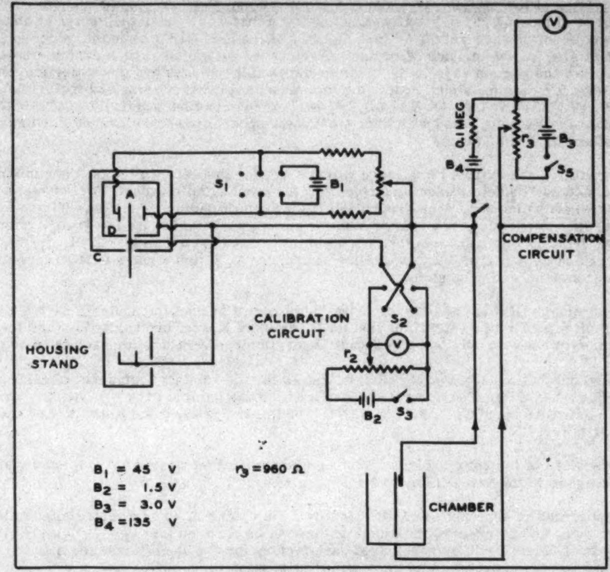

Fig. 1--Circuit for ionization meter

If the electrometer is set on top of one of the chambers, and a contactor connects the inner electrode plus the electrometer needle with the 135-volt source, the needle is at its zero positio As soon as the contactor is withdrawn at the beginning of each measurement the needle begins to drift, and the rate of the migration of the needle is proportional to the ionization current flowing between the discharging inner electrode and the grounded wall of the chamber.

Since the guard ring is at all times at practically the same potential as the inner electrode of the chamber (differing at the most by about ± 0.1 volt) all leakage losses are completely avoided.

Instead of observing the displacement of the needle per unit time, or "drift method," it is much more accurate to add gradually a compensating potential of from zero to three volts to the guard-ring potential by connecting it, and the housing of the electrometer, with a potentiometer circuit and adjusting the voltage continuously so as to keep the electrometer needle always nearly at the zero point.

This compensating voltage, acting by its induction effect on the floating system, is read in successive intervals of a few minutes on a precision voltmeter. If this voltage is divided by the number of seconds and multiplied by a carefully determined calibration coefficient, one obtains directly the ionization, q, expressed in number of ions, I, produced in the chamber per cm^3 per sec.

The advantage of using three geometrically similar cylindrical brass chambers as ionization vessels is described by me earlier [HESS, 1941]. It is only of importance if one desires to determine separately the ionization produced by cosmic rays, by local gamma rays, and from the walls of the chamber (background).

For the present purpose only one chamber is necessary, and the choice was made according to the activity of the samples to be studied.

Computation of the gamma ray ionization from radium, thorium, and potassium--A point-shaped source of gamma rays, quantity m, placed at a distance r from the center of an ionization chamber produces ions at a rate $q = K(m/r^2)e^{-\mu r}$, where K is Eve's constant, which has to be determined by using known amounts of radium, thorium, or potassium, and μ denotes the coefficient of absorption of the gamma rays in the medium between the source and the ionization chamber. Eve's constant for radium, slightly differing for vessels of different size and materials, was determined by V. F. HESS and EVA M. BALLING [1945] for the chambers actually used for the present study. For brass vessels, filled with nitrogen at atmospheric pressure, we obtained $K = 4.8 \times 10^9$ I per g of radium at unit distance.

If the radium is distributed in a large volume, as, for instance, in rocks, the gamma ray ionization produced can be determined by integration for a few simple cases. For example, if the ionization vessel is placed on even ground and its content of radium, thorium, and potassium is known according to chemical analysis or other methods, we have for the integrated effect of the gamma rays from radium, thorium, and potassium the three formulas $q_1 = 2\pi K_1 m_1/\mu_1$, $q_2 = 2\pi K_2 m_2/\mu_2$, and $q_3 = 2\pi K_3 m_3/\mu_3$, where the subscripts 1, 2, and 3 refer to the respective values for radium, thorium, and potassium.

In a monograph [HESS, 1934] on the ionization balance of the atmosphere I have shown that the gamma ray effects of radium itself, of radium B, uranium X, etc. are negligible, and therefore a simplified treatment with only one significant absorption coefficient μ for each term is permissible.

It is obvious that μ_1, μ_2, and μ_3 must be known for the hardest component of gamma rays in each case (RaC″, ThC″). The absorption coefficient of the gamma rays from potassium is, according to L. H. GRAY and C. T. P. TARRANT [1934], practically equal to the one of the gamma rays from RaC″.

Consideration of the softer components of gamma radiation would give only small and insignificant increases in the values of q_1 and q_2.

If an apparatus is surrounded on all sides by a very thick layer of a material containing radium, thorium, and potassium, the formulas have to be changed into $q_1 = 4\pi K_1 m_1/\mu_1$, etc. For rocks a layer of 50 cm could be considered satisfactory for the use of these formulas. With crushed rocks layers about twice as thick would be advisable.

The absorption coefficient μ_1 of the gamma rays from RaC″ was directly determined by putting a sealed radium tube in the center of a cylindrical box containing crushed granite and measuring the ionization at a large distance with different thicknesses of the absorbing layer of crushed granite. Eva Balling obtained thus a value for the absorption coefficient of crushed granite (density 1.34 g/cm^3) of $\mu = 0.057$ cm^{-1}. The mass absorption coefficient resulting, 0.0426 cm^2/g, agrees well with the usual mean value, 0.045, for the gamma rays from RaC″.

In the formulas given above m_1, m_2, and m_3 denote the contents of radium, thorium, and potassium per cm^3 of rock. Because of the fact that these contents are usually given in g of Ra, Th, K per g of rock, it is convenient to transform these formulas by introducing $M_1 = m_1/\rho$, $M_2 = m_2/\rho$, and $M_3 = m_3/\rho$, where M_1, M_2, and M_3 denote the radium, thorium, and potassium content per g of the rock sample. Thus we have, immediately above an infinite plane surface of rock, $q_1 = 2\pi K_1 M_1 \rho/\mu_1$, $q_2 = 2\pi K_2 M_2 \rho/\mu_2$, and $q_3 = 2\pi K_3 M_3 \rho/\mu_3$. This has the further advantage that we need only the mass-absorption coefficients μ/ρ, etc., which are much better known and practically constant for all materials.

Eve's constant for thorium and potassium--The constant K_2 for thorium has never been determined. For this reason, in my previous article on the radioactivity of rocks [HESS, 1941] I had to make the bold assumption that the contribution of the gamma rays from thorium and its products to the total ionization of the atmosphere near the ground is equal to the ionization from the uranium-radium products. A. S. EVE [1911] used the same assumption.

The lack of data on thorium was due to the fact that no radium-free thorium standard was available which was old enough to be in equilibrium with mesothorium and radiothorium. After a futile waiting of about two years I finally decided to use a powdered sample of a thorium mineral, free of uranium, as a standard, upon a suggestion from the Swiss geologist H. Hirschi.

The National Bureau of Standards in Washington recently provided for this purpose a sample of 104.6 g of thorite in a sealed glass tube 18 cm long and two cm wide. This sample contains 9.61 per cent thorium and only 0.5 per cent uranium.

The gamma radiation from this tube was easily measurable with the ionization meter at distances from 30 to 100 cm. The absorption curve taken with layers of from zero to 22 mm of lead showed after the first six mm a homogeneous hard gamma radiation with an absorption coefficient in lead of $\mu = 0.472\ \text{cm}^{-1}$ or $\mu/\rho = 0.0418\ \text{cm}^2/\text{g}$, which is characteristic for ThC″. The soft component which at zero thickness produced 23 per cent of the total ionization gave $\mu/\rho = 0.71\ \text{cm}^2/\text{g}$.

Preliminary experiments in May 1946 give, after correcting for the small gamma ray effect of the 0.5 per cent uranium content, for Eve's constant for thorium the value $K_2 = 742$ I per g thorium, at unit distance.

The corresponding value K_3 for potassium can only be estimated. According to Muelhoff [EVANS and GOODMAN, 1941] one g of potassium gives off 23 beta rays per sec. GRAY and TARRANT [1934] found that three photons are emitted for every 100 disintegration electrons. From this it follows that one g of potassium emits 0.69 gamma ray photons of about 2×10^6 electron-volts energy, which corresponds to an emission of 2.2×10^{-6} ergs/sec.

The total number of ions produced by these photons, N, would be $(2.2 \times 10^{-6})/(5.1 \times 10^{-11}) = 4.32 \times 10^4$ pairs of ions/sec. Thus $N = \int_0^\infty K_3(e^{-\lambda r}/r^2)4\pi r^2 dr = 4\pi K_3/\lambda = 4.32 \times 10^4$ I, where λ denotes the absorption coefficient of gamma rays in air. Taking this as $4.5 \times 10^{-5}\text{cm}^{-1}$, one obtains Eve's constant for potassium, $K_3 = 0.154$ I per g at unit distance.

Another way of deriving K_3 was used in my previous publication [1941]: If we adopt data from Gray and Tarrant as the most reliable, one g of potassium would be equivalent in its gamma ray effect to 1.6×10^{-11} g of radium. Thus, for our brass cylinders the value $K_3 = 1.6 \times 10^{-11} \times 4.8 \times 10^9 = 0.077$ I/g results. The two values differ considerably. Since, however, the potassium content of most granites is only from 0.02 to 0.04 g per g of rock, it is of no great importance if we choose the higher or the lower value. A rough mean value of $K_3 = 0.12$ I/g at unit distance will be accurate enough for our present purpose.

Computation of the ionization produced by the gamma radiation from Quincy granite--With the foregoing data one can compute separately the ionization produced by the uranium-radium, the thorium products, and by potassium for any type of rock.

EVANS and GOODMAN [1941] give the uranium content as $(2.7 \pm 0.5)10^{-6}$ g per g of granite for Quincy granite taken from Swingle's quarry. This in equilibrium with radium corresponds to 0.95×10^{-12} g of radium per g of rock. Therefore $q_1 = 2\pi K_1 M_1 \rho/\mu_1 = 6.28 \times 4.8 \times 10^9 \times 0.95 \times 10^{-12}/0.045 = 0.64$ I. Similarly, the thorium content of Quincy granite as given by Evans and Goodman, namely, $M_2 = (8.1 \pm 2.0)10^{-6}$ g Th/g leads to a value $q_2 = 6.28 \times 742 \times 8.1 \times 10^{-6}/0.041 = 0.92$ I. For the potassium content, choosing a mean value of 0.03 gK/g we get $q_3 = 6.28 \times 0.12 \times 0.03 = 0.50$ I. The sum of the three components of ionization therefore is $q = q_1 + q_2 + q_3 = 2.06$ I. This would represent the total ionization to be expected over a large surface of Quincy granite.

For comparison with the actual observations, see Table 1. Surrounding an ionization chamber on all sides with an infinite layer of the same material we could, of course, expect a value of q twice as high as the one given, that is, 4.12 I.

Observations in the quarry--Observations were carried out by F. A. Benedetto and the author in the quarry of Swingle Company, Quincy, Massachusetts, in August 1945. The granite quarried there is very homogeneous; the shade of coloration differs slightly, but we could not detect any difference in the gamma radiation from the dark grain, medium grain, and light grain specimens.

First the ionization chambers with the panel box were set up directly on the horizontal surface of a large slab of granite 8 ft × 4 ft × 3 ft. Then the apparatus was placed on a card table and the table set up on top of the same block of granite. The results are listed in Table 1. The figures given represent the net ionization produced by the gamma rays from the rock, after subtracting the average ionization by cosmic rays, air radiation due to radioactive products in the atmosphere, and the residual ionization from the inner walls of the chambers. These three effects together amounted to 3.21 I for the large chamber, 3.36 I for the medium chamber, according to numerous experiments over water, made on a wooden pier in New York, performed in the summers of 1944 and 1945.

In another experiment, the apparatus standing on the card table was set up directly on the ground, which consisted of crushed granite with a slight admixture of humus. The ionization observed here was only slightly smaller (5.18 I) than above the solid block of granite (5.57 I).

Table 1--Observations in Swingle's quarry, Quincy, Massachusetts, of ionization produced by gamma rays from Quincy granite

Apparatus standing on large granite block, 8 ft × 5 ft × 3 ft	5.95 I
Apparatus on card table, set up on the same block of granite	5.57 I
Apparatus on card table, set up on the crushed granite	5.18 I
Apparatus on card table, standing in iron boat above crushed granite	4.29 I
Computed gamma ray ionization, taking Evans and Goodman's figures for the uranium and thorium content and three per cent potassium content (0.64 I, 0.92 I, and 0.50 I)	2.06 I

In order to find out whether these unexpected high ionization values were due to softer rays penetrating through the 2.5 mm brass walls of the chambers, a special experiment was performed in which the apparatus, standing on the card table, was placed in a large iron boat, resting on the ground, over crushed granite.

Such boats are used in the quarry for lowering a crew of workers into a deep pit in order to drill the holes for subsequent blasting. The walls of the iron boat were about 1.2 cm thick. The shape of the boat is a half cylinder, open on one side, of about six ft diameter. The mean ionization in the boat was only slightly less than on the ground. The absorption coefficient in iron, computed from this experiment, was 0.16 cm^{-1}, indicating that only gamma rays were involved. Naturally, this coefficient is not very accurate, since the boat was open on one side while one end consisted of perforated iron plating. However, the coefficient is of the right order of magnitude, indicating that our results are not falsified by softer radiations emitted by the granite.

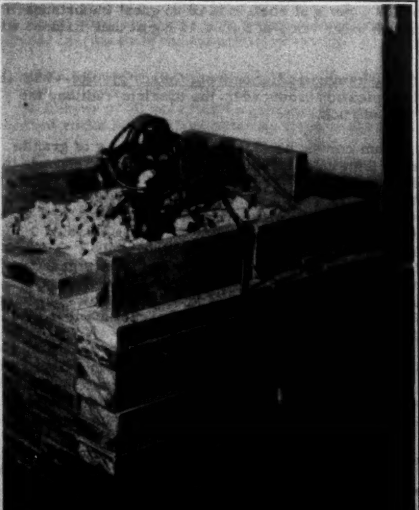

Fig. 2--Ionization chamber surrounded by crushed granite and shielded by iron bars

A comparison with the figures computed from the uranium, thorium, and potassium content shows a very large discrepancy: The observed ionization is more than twice as great as the computed value.

This finding, now substantiated in a very well defined special case (Quincy granite) corroborates the conclusion drawn by the author [1941].

Laboratory experiments--It seemed advisable to investigate this discrepancy further by experiments with crushed granite, so in the autumn of 1945 the Swingle Company in Quincy shipped to Fordham, upon my request, 400 lb of crushed dark-grain granite in bags. This quantity was used for another set of measurements in which the ionization chamber--the medium or the small one--was surrounded on all sides with a 21 cm layer of crushed granite while the local gamma rays from the walls of the room were completely absorbed in a layer of ten cm of iron. First the chamber, with the electrometer on top, was set up in the empty "iron house" built up from iron bars on the bottom and on all sides and leaving only the top open for the electrometer and microscope (see Fig. 2).

The background ionization observed before the granite was added was 4.01 I due to cosmic rays, filtered through four floors and ceilings, local gamma rays from the ceiling of the room above the iron house, and the residual radiation.

Then the space between the iron bars and the ionization chamber was filled completely with crushed granite. The average thickness of this layer was 21 cm. The total ionization observed in this case was 9.71 I, based on the average of experiments on many days.

Thus the effect of the 21 cm layer of crushed granite was 9.71 - 4.01 = 5.70 I. A graphical integration of the open cone on top of the chamber shows that in the experiment the solid angle subtended by the granite layer amounted to $4\pi \times 0.85$ sterradians. A complete concentric layer (spherical shell 21 cm thick), therefore, would give 5.70/0.85 = 6.68 I.

Since the mean absorption coefficient of gamma rays in the crushed granite was determined directly (0.057 cm^{-1}), one can now extrapolate to infinite thickness by using my formula [1922].

$$q_{\infty} = 4\pi KM(1 - e^{-\mu d})\rho/\mu \quad \ldots\ldots\ldots\ldots \quad (1)$$

where d = 21 cm. This gives q_{∞} = 9.5 I, as the extrapolated value of the ionization produced by an infinite layer (see Table 2).

The comparison with the computed value of 4.12 shows again very decisively that the observed ionization cannot be explained from the reported values of the uranium and thorium content of the granite.

Table 2--Observations of ionization produced by Quincy granite surrounding ionization chamber

Ionization produced by a layer of 21 cm of crushed granite (directly observed)	5.70 I
Corrected for open cone on top	6.68 I
Extrapolated for granite layer of infinite thickness	9.50 I
Computed ionization taking Evans' and Goodman's figures for the uranium and thorium content and three per cent potassium content (1.28 I, 1.84 I, and 1.00 I)	4.12 I

Discussion--Since both the field experiments and the laboratory measurements in the iron house show that the ionization actually produced by the gamma rays from Quincy granite is at least twice as great as the computed values, one is confronted with a serious difficulty.

At first one may be tempted to assume that "back-scattering" of cosmic rays on solid ground may be responsible for the observed surplus ionization. It would be conceivable that this effect, well known from experiments with Geiger-Mueller counters, is responsible for part of the difference in ionization of closed vessels placed over land and over water. However, this effect would be expected to be of much smaller magnitude, since the total ionization produced by cosmic rays amounts to only 2 I at sea level.

Furthermore, the back-scattering of cosmic rays is certainly not less over other soil materials such as gravel and sand, while the author, from his experiments at Spray Beach, New Jersey in August 1944, found that dune sand produces an ionization of only 0.5 I. This is in good agreement with expectation, since dune sand contains one tenth as much radioactive materials as volcanic rocks such as granite.

Thus only two possibilities remain: Either the uranium and thorium content reported by Evans and Goodman is much too low--one hesitates to make this assumption in view of the great care and improved technique employed by these authors--or one has to assume that granite, and perhaps most of the other rocks, emits a penetrating radiation of unknown origin.

One might think of penetrating radiation accompanying the fission produced by cosmic rays in the uranium and thorium contained in the rocks, but such an effect would be much too small, on account of the rarity of such events.

Another remote possibility would be artificial radioactivity induced by cosmic radiation, but this could be easily found out by performing the "iron house experiment" in a deep mine.

It is hoped that further experiments will lead to a satisfactory decision.

Acknowledgments--War conditions greatly delayed the completion of this work, which has been in progress since 1943. The Department of Terrestrial Magnetism, Carnegie Institution of Washington, did its best to further its progress.

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MILITARY OCEANOGRAPHY IN TACTICAL OPERATIONS OF WORLD WAR II

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(Contribution no. 354 from the Woods Hole Oceanographic Institution)

Introduction--Three years ago an announcement was made [see "References" at end of paper, SEIWELL, 1943] that military applications of oceanography were then being carried out in the War Department to obtain relevant data for the planning of long-range military operations. The Military Oceanographic Organization was, at that time, established in the First Weather Directorate of the Army Air Force Headquarters. Justification for its existence was centered in the close relationship between oceanography and meteorology and in the provision of oceanographic data to the long-range weather forecasting research program. Circumstances, however, soon changed the original plan, and after a reorganization, the newly-installed Weather Service initiated action to have the Oceanographic Unit transferred to the jurisdiction of the United States Navy.

The early work of the Military Oceanographic Unit determined the oceanographic organization which later operated in both European and Pacific theaters. The experience gained by this early organization, at a time when military operations were rapidly expanding, and when new tactical principles were being introduced, provided the basic ideas for an organization which in scope and operational influence exceeded anything visualized early in 1943. Military oceanography came into being with the new type of amphibious warfare. Its early development was hindered by a failure to realize that the then-established tactical conceptions would change in accordance with the new type of warfare. It was not until disastrous mistakes in early amphibious assaults were brought to light that the idea of an oceanographic concept of amphibious warfare was recognized.

Organization of military oceanography

Military oceanography is divided into two broad categories; (a) the development of field and laboratory techniques for obtaining new oceanographic information and (b) the analysis and presentation of relevant oceanographic information for military planning. (a) is concerned with the development of instruments and equipment for obtaining information on the tides, currents, state of the sea, and other hydrographic factors, methods of forecasting state of the sea and surf, and methods for interpretation of photographs for hydrographic information. (b) embraces the analysis and presentation of all types of oceanographic information for specific military planning. It has two phases--the strategical and the tactical.

The strategic oceanographic report has as its object a demonstration of the main overall hydrographic factors affecting the location and timing of a long-range operation. The work is carried out at the highest headquarters.

The tactical oceanographic report has as its object the provision of detailed hydrographic information to combat commanders in the field, showing the relationships of hydrographic factors to the operational plan, and, specifically, their effect on the personnel, equipment, logistics, and timing at specified locations. The data are presented in forms suitable for rapid interpretation and are prepared most satisfactorily at a high field headquarters.

Organization for the tactical phase of military oceanography--This paper is concerned with the tactical phase of military oceanography and is based on the organization and work of the military oceanographic team which operated first in the European and later in the Pacific Theater.

Experience with the planning of the major amphibious operations during the War has brought out the fact that tactical oceanographic work is best handled by a small, well-integrated unit of experts working in close liaison with field headquarters. The team is equipped for combat. It is prepared to land with assault troops to be available to make surveys for the future buildup and for the logistical development of captured beach areas during the early critical stages. It includes trained aerial and ground reconnaissance personnel as well as a scientific staff with supporting technicians.

The team was provided with a photographically equipped aircraft (B-25) and with surface craft (DUKWS and LCCS). The increased liaison facilities afforded by this equipment made for better cooperation with established field reconnaissance organizations.

A high degree of cooperation was maintained within the team. All personnel, regardless of status, were given training in the basic principles of oceanography, and were cognizant of the methods and techniques employed. Key personnel who had access to operational plans had the responsibility of processing all final data and of estimating its significance to landing craft and other assault instruments.

Services of a tactical military oceanographic unit

The following breakdown of services was provided by a military oceanographic team to an operation in the combat zone; (a) the planning and training phase, (b) the assault phase, and (c) the buildup and supply phase.

The planning and training phase--This phase involves five services, as follows:

1. Special beach and hydrographic charts for specific locations were generally prepared by adding information to existing hydrographic charts and redrafting to suitable scales. The additional information was partially taken from publications, but a certain amount was always obtained by local reconnaissance. As the latter was usually restricted to the air, methods were developed to estimate beach gradients, underwater depths, and other hydrographic factors from aerial photographs. The charts show the following information for the target beaches; physical state of the beach, beach gradients, beach composition with reference to trafficability and road-building materials, suitable landing-craft areas, beach exits, and landing-craft hazards.

2. Twelve and 24-hour forecasts of state of the sea and surf in the vicinity of target beaches. This represents one of the major wartime developments in military oceanography. The initial research was instigated by the Military Oceanographic Unit during the planning stage of the Northwest African invasion (operation TORCH). The method finally devised was chiefly a result of the work of the Director of the Scripps Institution of Oceanography, called in at the request of the Military Oceanographic Unit. Although the earlier method did not play toc prominent a role in the landings, its possibilities were realized, and stimulation of research on surface conditions of the ocean eventually led to the development of the present reasonably accurate method of forecasting the state of the sea and surf for any part of the World's oceans.

3. Preparation of a Daily Hydrographic Bulletin giving, in tabular form, a 24-hour hour-by-hour forecast of the probable hydrographic conditions affecting assault craft and other invasion equipment along target coasts. For its preparation, results of measurements on beach gradients, underwater depths, and the operational drafts of specified landing craft were combined with tidal predictions and state of the sea forecasts and other relevant hydrographic data. The final result was a reasonably complete condensation of hydrographic conditions as they might be expected to affect invasion equipment on the target. Hourly data were given for the following; height of surf, period of surf, depth of water at breaking surf, number of lines of surf, distance from breaking surf to first available cover on beach, relationship of grounding of landing craft to breaking surf, height and period of waves between line of departure and beaches, height and period of waves at locations of transfer of personnel from transport to landing craft, direction and velocity of surface currents, estimated drift of landing craft (velocity and direction) between line of departure and beach, degree of solar illumination, air temperature, distance from grounding of landing craft to nearest available cover, and depth of water over enemy defenses.

4. Preparation of tidal illumination diagrams. These were originally devised by the Oceanographic Unit for the early amphibious operations. They showed diagrammatic relationships between times of high and low tide and the degree of solar illumination. The three types of twilight are indicated so as to bring out gradation of light from sundown through darkness, as well as from darkness through sunrise.

5. Consultants for all other military oceanographic matters.

The assault phase--The oceanographic team lands with the assault troops to be available for consultation and liaison purposes and to make essential surveys and observations. Preparation and dissemination of the Daily Hydrographic Bulletin was continued.

The buildup and supply phase--This phase involved the following five services: (1) Surveys of beaches to determine most suitable locations for unloading different classes of supplies from landing craft; (2) continuation of forecasts of sea and swell, specifically interpreted in terms of the supply program; (3) special surveys to determine locations for removal of sand, gravel, and other road-building materials from the beach, with special attention to exit points; (4) preparation of tables showing hourly depths of water over critical sills; and (5) special hydrographic surveys for forecasting state of the sea.

Military oceanography in the European Theater of Operations

In the spring of 1944, the Chief of the Military Oceanographic Unit of the Army Air Forces was ordered to the European Theater of Operations as Consulting Oceanographer. At that time, special charts of the Normandy target beaches were in preparation, and a sea-swell forecasting service had been set up in the Theater. However, early discussions with staff officers of Theater Headquarters and the First United States Army indicated that the separate hydrographic services in the Theater should be coordinated, and that a daily hydrographic bulletin and tidal illumination diagrams should be prepared for the Normandy targets. To accomplish this a small group of personnel was hastily organized in the office of the Chief Engineer of the European Theater early in May, 1944.

For the assault phase, the Theater Oceanographer was attached to the forward headquarters of an engineer group, and plans were made to provide him with limited personnel in France after the initial beach landings. Preparation of the Daily Hydrographic Bulletin just previous to and during the initial assault stages was carried out by two specially trained meteorological officers while afloat. The assembly of the oceanographic personnel on Omaha Beach in the early stages of the assault initiated the first oceanographic combat team in history.

In the early days of the Normandy operation, the Military Oceanographic Unit performed a variety of duties in connection with the organization of the beaches and their logistical development. In addition to preparing on-the-spot forecasts of state of the sea and surf for the early critical supply and buildup operations, survey parties were organized on both Omaha and Utah beaches to obtain hydrographic data (beach topography, tides, currents, surf, etc.) for comparison with prelanding information and for the use of the beach organizations. Other surveys were made to estimate the effects of removal of beach shingle on the roadways and exit points. Studies were undertaken to determine the effects of wave heights on cargo operations. The inverse relationships between wave heights and tonnage unloaded were worked out for the DUKW operations between shore and the cargo ships moored in exposed anchorages.

In the latter part of August, 1944, oceanographic headquarters were set up in Paris. An Oceanographic Section was then formally established in the Office of the Chief Engineer, and personnel increase of American military and French civilians was sufficient to take care of the work. Two French Naval officers were attached for liaison with the French Hydrographic Office. Military personnel of the Oceanographic Section formed the nucleus for the 6812 Engineer Technical Intelligence Team--Oceanography and Beaches, activated in the European Theater of Operations in December 1945. Because of the large number of practical tidal problems with which the Oceanographic Section became involved, the United States Coast and Geodetic Survey loaned the Chief of its Tidal Division for four months' duty. The work of this officer was invaluable in formulating the practical tidal problems with which port operations were confronted and in clearing the confusion which had resulted from the various tide tables in circulation.

Near the end of the winter of 1944-45, key personnel of the Oceanographic Section were ordered to the United States to constitute the nucleus of a military oceanographic organization for the Pacific Theater.

Military oceanography in the Pacific Theater

The problems posed by the request of the United States Army Headquarters in the Pacific Ocean areas for a Military Oceanographic Unit to be organized and trained for duty in that Theater chiefly concerned the procuring of suitably trained personnel. At that time (1945) technically trained personnel were established, and there was known to be a serious shortage of the type required for this unit. It was with this in view, as well as to obtain information on Pacific Theater requirements, that the Commanding Officer of the European Theater Team was ordered to the Pacific shortly after returning from Paris. After conference with the staff of Pacific Headquarters he returned to the continental United States with orders to procure, organize, and train a Military Oceanographic Unit from material available.

The strength of the new Military Oceanographic Unit was fixed at 61 officers and men. In addition to the Commanding Officer and Adjutant, its personnel were divided as follows: (a) 17 oceanographers, meteorologists, and geologists; (b) 19 aerial photographers, phototopographers, and photo interpreters; (c) 15 draftsmen, computers, and technicians; and (d) eight clerks and stenographers.

One of the officer meteorologists was a rated pilot who flew the Unit's photo-equipped B-25 aircraft. Other personnel were selected on the basis of their technical training, as well as previous backgrounds of marine engineering and seamanship. Their additional duties included operating the Unit's surface craft.

Screening of officers and men for suitable qualifications began in April, 1945, and in May, 1945 the complete Unit was assembled at Orlando, Florida, for one month of intensive training in aerial photographic methods and physical oceanography. Training in physical oceanography consisted of a series of lectures by the leading physical oceanographers in the country, including the Directors of the two Oceanographic Institutions.

After arrival in the Pacific Theater the Military Oceanographic Unit was attached to the highest headquarters of the Olympic assault operation. Key personnel were placed in contact with operational staffs of the various task forces. At the War's end the Unit was in the process of assembling and analyzing oceanographic and beach information pertinent to the accepted assault plans. New information was acquired from special studies of aerial photographs obtained from Theater Intelligence agencies. If the Olympic operation had been carried out, part of the Unit would have landed on the beaches with the assault troops so as to undertake special hydrographic and beach surveys for the logistical development of the beach areas and to check pre-landing information. The remainder of the Unit was to remain afloat and prepare state of the sea forecasts and other pertinent information for use in the early buildup stages. The project was similar to the oceanographic plan of the Normandy operation. It was more complete because of increased personnel and the background of experience gained from that operation.

Although active warfare in the Pacific ended before the Military Oceanographic Unit got into combat, a part of it participated in a practice maneuver with a combat infantry division in training for the Japanese assault. The following brief description of the oceanographic service provided for this maneuver may help clarify the picture of an organized oceanographic service in actual combat.

The maneuver took place on a Pacific island previous to V-J day. The plan called for a regimental combat team to assault a specified beach with two battalions abreast. After securing of the initial beachheads, it was to hold and defend until passed through by the reserve regimental team. The Oceanographic Service was designed to provide pertinent pre-landing data for use in the maneuver, and trained personnel in the exercise pattern, whose duties were to keep the Commander and staff informed of impending sea conditions between the transport areas and the beaches, and of surf conditions on the target.

The distribution of personnel was that one oceanographer remained on the command ship; two state of the sea forecasters were stationed at a Weather Central, and two state of the sea observers landed with an early assault wave. During the principal day of the maneuver, a member of the Oceanographic Unit photographed the exercise from the air.

The duties of the individuals were as follows: Oceanographer, on board the command ship, prepared a Daily Hydrographic Bulletin showing the expected hour-by-hour states of the sea, tides, and currents and their effects on the types of landing craft in use. He also informed the Command Staff of impending changes in sea conditions affecting the operation; two state of the sea observers, landed with an early assault wave to observe heights, periods, and wave lengths of sea and surf on the target beaches, and to note the effects of sea conditions on landing craft. Their observations were transmitted by the shore party message center to the command ship, from where they were relayed to the Weather Central for use of the state of the sea forecasters; two state of the sea forecasters, on duty at a distant permanent Weather Central prepared 24-hour state of the sea forecasts every 12 hours for transmission to the oceanographer on board the command ship.

The forecasts were made daily and radioed to the Infantry Division Message Center at $12^{h}00^{m}$ and $24^{h}00^{m}$. The noon forecasts covered the 24-hour period from $18^{h}00^{m}$ of that day until $18^{h}00^{m}$ the following day. The night forecasts covered the 24-hour period from $06^{h}00^{m}$ to $06^{h}00^{m}$ the following day. Information on the state of the sea was available continuously throughout the entire period of the maneuver. Each forecast was a 24-hour prognosis of state of the sea and surf for the areas concerned.

After cessation of hostilities the entire Oceanographic Unit was reassembled at a rear headquarters in the Pacific and a three month oceanographic research program undertaken. This program was planned to take stock of the characteristics and limitations of certain selected aerial methods for measuring underwater depths and of methods for forecasting sea swell and sea surf. Both of these had obtained vital operational importance during the recent War, and military oceanographers had encountered various perplexing problems during operational use. The methods had been developed under conditions of war expediency as a means of obtaining hydrographic data, and the normal peacetime scientific procedures were altered in the interests of expediency. Often practical rule of thumb methods were devised at the sacrifice of adequate recording and experimentation. During the War the results justified the means.

Three months were spent obtaining pertinent observations and reducing them in an elementary fashion. It was originally planned that a comprehensive analysis of the results would be undertaken when facilities were available for the necessary scientific coordination. To date, one study dealing with an appraisal of the Sonne Stereo camera for underwater depth determination has been published [BEACH INTELLIGENCE UNIT, 1946]. It is desirable that a thorough investigation be made of technical methods developed during the War and recorded for future scientific and military study, as well as for an appraisal of their application to peacetime problems.

The future of military oceanography

The peacetime development of scientific military methods and counter measures for future wars will undoubtedly decide the fate of this Nation. The power of modern science applied to instruments of warfare over previous standardized strategical and tactical doctrines has been aptly demonstrated. Little imagination is required to visualize the necessity that this Nation maintain a superior scientific military research program.

Oceanography embraces all studies on the oceans of the world. Military oceanography is the application of this information to military strategy and tactics and appears to be a sphere of investigation inseparable from future military developments. The archaic conception that the science of oceanography falls exclusively within the province of naval operations is admission of lack of vision and imagination. Thus, the greatest operations of the recent War were the so-called "combined operations" in which Army, Navy, and Air Forces operated under a single unified command. Because these operations were assaults on enemy coastal areas, initial problems concerned the military oceanography of the target, and the complexities of planning and execution of the operation were definitely lessened when individual unit commanders were cognizant of the oceanographic picture. The rapid development of amphibious warfare caused the tactical picture to change too rapidly for rigid application of a science with which few persons were familiar. One of the results was that military commanders in coastal areas were confronted with oceanographic problems which they were not only unable to solve, but were frequently unable to formulate.

It is no secret that Army-Navy coordination leaves much to be desired. Military oceanography provides a common meeting ground, and military personnel aware of what can be accomplished are better prepared to recognize the problems of marine operations and assist in formulating a mutual strategy in harmony with the natural marine barriers. A special Military Oceanographic Service no more duplicates the functions of a parallel Naval Service than do other Army and Navy separate technical services.

A partial solution to the present situation appears to be found in an active liaison between professional oceanographers and regular military personnel. Since there are no longer established oceanographers in the regular military service, accomplishment of contracts with the established civilian oceanographic institutions is advisable as an economical means of training selected officers and for specific military research projects. If the proposed merging of Army and Navy into a single command is to accomplish improved coordination and cooperation, overlapping training of staff and combat officers need be accomplished. Oceanography is the science to contribute most to the intelligent perception of mutual problems so essential in joint staff planning of operations and in their execution.

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THE USE OF MEAN SEA LEVEL AS A GEOPHYSICAL DATUM

H. A. Marmer

The concept of mean sea level is very simple--in fact, self-explanatory. The appearance of the surface of a body of water at rest is a common experience, whether the water be in a bucket, a tank, or a pond. If the surface is disturbed, the level of the water at any point oscillates about its position of rest, which is conceived as its mean level. In the same way, the oceans constitute a huge, irregularly-shaped body of water whose surface is disturbed by one cause or another so that its level at any point is constantly changing in elevation. And we conceive mean sea level at any point along the shore as the level of the ocean waters at that point, were they at rest.

By implication, then, the determination of the datum mean sea level appears a simple matter. All that need be done, apparently, is to measure the changing level of the surface of the sea at any point for some time and derive the average or mean position. But when we are actually confronted by the necessity for a precise determination of mean sea level at any place, the problem is found to be not quite so simple.

To begin with, we must note that in determining mean sea level at any point, we are determining not a scale reading on an instrument with a fixed zero, but the location of a horizontal plane on the face of the Earth. To be sure, a tide staff is used in measuring the changing level of the surface of the sea; but the scale reading on the tide staff is a wholly arbitrary number which has meaning only when related to some fixed point on the land. This means that the tide staff used must be carefully referenced to a number of adequate bench marks. And this matter cannot be too strongly emphasized.

The changing level of the sea is most effectively recorded by an automatic tide gage. Such a tide gage record, calibrated by comparisons with a tide staff adequately referenced to bench marks, furnishes the basis for determining mean sea level.

The level of the sea at any point is at all times subject to disturbing influences--of tide, waves, wind, currents, atmospheric pressure. Variations in temperature and density of the water

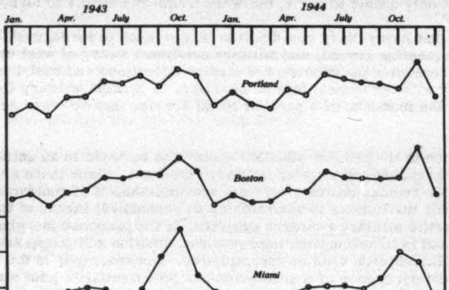

Fig. 1--Monthly sea level at four stations along the Atlantic coast likewise introduce disturbing factors, and near the land, rainfall and runoff must be added. Of these the tide is generally the predominating factor, and since the tide is periodic with a period of about 24 hr, we can get a first approximation to mean sea level by averaging the changing level of the sea over a period of 24 hr, which practically eliminates the tide.

If we determine the sea level any place for a day, we find that it changes from day to day--sometimes by as much as several feet. This is not surprising in view of changing meteorological conditions, but even if we derive sea level for a month we find relatively wide variations from month to month. In Figure 1 are shown the monthly sea levels at four stations along the Atlantic coast for the two-year period 1943-1944.

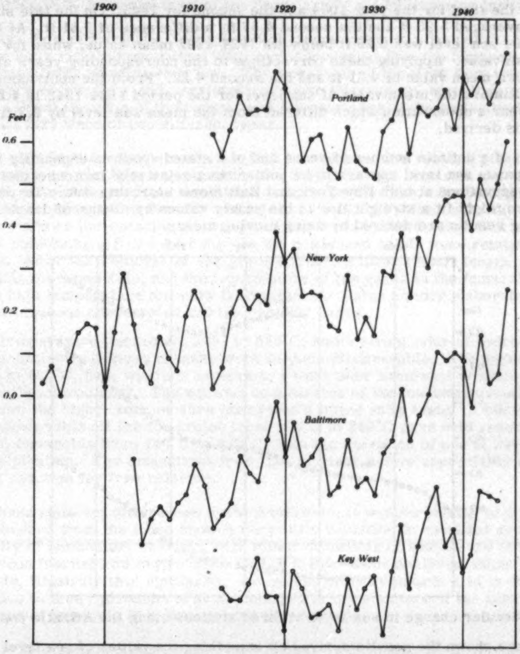

Fig. 2--Yearly sea level at four stations along the Atlantic coast

Differences of as much as half a foot or more are seen to have occurred in the sea level from month to month. If we investigate the matter further, we find that there is a large element of periodicity of a seasonal nature in the variation of monthly sea level, so that a month of observations does not determine mean sea level with any precision.

If we take a year of observations, we find variations from year to year of several hundredths of a foot to more than a tenth of a foot, as Figure 2 shows. And within a ten-year period two yearly values may differ by more than a quarter of a foot.

In determining the datum of mean sea level at any place it has been customary to take the average level for whatever period was available and call it mean sea level. Clearly, considerable discrepancies arise from such a procedure, depending on what years are used. For example, at New York if the five-year period 1904-1908 is used, we would get a value nearly half a foot lower than if the five-year period 1941-1945 is used, and if the mean sea-level datums at two places are connected by precise levels, we may get exactly opposite results as to their relative elevations. For precise results, therefore, it appears that some definite number of years should be used for determining mean sea level, and, furthermore, that some definite epoch should be adopted.

In the development of the tide-producing force there is a small variation of sea level depending on the longitude of the moon's node, which has a period of 18.6 yr. Hence we may take 19 yr of sea-level observations as constituting a primary determination of that datum. As for epoch, any epoch agreed upon will do, and in the United States Coast and Geodetic Survey we are using the epoch 1924-1942. With the adoption of a given epoch, we can correct short series of sea-level observations to a mean value and to the given epoch by comparison with a primary determination at some suitable place. For example, suppose we had two series of observations at Baltimore, each one yr in length, the first for the year 1904 and the second for 1945. On the tide staff at Baltimore the first series averaged 3.96 ft and the second 4.57 ft, a difference of 0.61 ft. At New York it is found that for 1904 sea level was 0.25 ft below its 1924-1942 mean value, while for 1945 it was 0.29 ft above that mean value. Applying these corrections to the corresponding years at Baltimore, the first series gives a mean value of 4.21 ft and the second 4.28. From the continuous series of observations at Baltimore the mean value of sea level for the period 1924-1942 is 4.25 ft, so that by correction of a year's observation which differed from the mean sea level by 0.3 ft a value correct to within 0.04 ft is derived.

The adoption of a definite number of years and of a stated epoch is especially important at the present time, because sea level appears to be subject to a relatively large secular change. The long series of observations at both New York and Baltimore bear this out. To determine this secular change we might fit a straight line to the yearly values by means of least squares.. But more illuminating results are derived by using moving means.

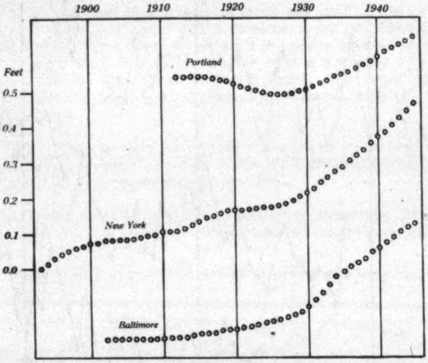

Fig. 3--Secular change in sea level at three stations along the Atlantic coast

In Figure 3 are shown the results derived by smoothing the values of sea level at three stations by moving means. At Baltimore, for example, sea level appears to have changed only 0.06 ft from 1902 to 1927 or at the rate of about a quarter of a foot per century, while from 1927 to 1945 the change was 0.27 ft or at the rate of about 1.5 ft per century. At New York the change in sea level likewise appears to be considerably greater since 1927 than previously. At Portland secular change in sea level is somewhat more complicated than at the other two stations, but the upward trend since 1927 is unmistakable. This secular change in sea level makes it all the more important to fix the datum of mean sea level with precision by defining both the length of series and the epoch used. With accurately referenced tide observations and with the adoption of 19 yr as the length of series and the use of a definite epoch, mean sea level becomes a precise geophysical datum.

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PRIMARY SUBLIMATES AT PARÍCUTIN VOLCANO

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The first lava flow of Parícutin Volcano, which began within two days of the birth of the Volcano, was particularly rich in fumaroles. With each succeeding flow the fumaroles decreased in abundance, the later flows showing very few. The fumaroles of the first flow were concentrated about the periphery of the lava and persisted for more than a year, when they were covered by later lava flows. From the odor of their gases and the character of the salts about their orifices, it was obvious that they were of two different types.

In order to sample the volatile materials that issued from the vents, a glass tube 2.5 cm in diameter and about a meter long was placed in the orifice of the fumarole and the vent banked with ash, so that the volatile products would escape through the tube. Steam began to condense immediately in the coolest part of the tube and sublimed solids to collect near the fumarole end. Field tests were made on the escaping gases by passing these gases through test tubes containing appropriate test solutions. After a 24-hour run the condensed solids were removed for analysis in the laboratory. After the removal of the glass collecting tube, a short length of glass tubing was introduced into the same hole, and the temperature of the gases in the fumarole chamber was measured with a high temperature mercury thermometer. Later a more elaborate train was used to collect both the aqueous condensates and the residual gases.

The lowest temperature fumaroles, 105° to 240°C, had a strong odor of hydrochloric acid, and the gases were sufficiently noxious to make work in them disagreeable. The higher temperature fumaroles, 240° to 430°C, had, with one exception, a weak odor somewhat reminiscent of guano or were even distinctly ammoniacal. The aqueous condensates of the low temperature fumaroles had a strong acid taste; the higher temperature fumaroles a biting salty taste. A tabulation of the tests upon the gases showed that all the fumaroles from 105°C to 240°C gave acid reactions with methyl-red, while all the fumaroles from 240°C to 430°C, with the exception of one at 294°C yielded gases alkaline to phenolpthalein. The emanations from two fumaroles gave appreciable reactions for lead and one a strong reaction for free chlorine.

In view of these apparent differences in the fumaroles, it was surprising to find that the solid condensates recovered from the tubes showed very little variation in chemical composition. They consist essentially of ammonium chloride, with minor quantities of sodium and potassium chloride, fluorine, and silicon (perhaps as cryptohalite $2NH_4F.SiF_4$). Four analyses, taken at random from ten analyses made, illustrate this similarity. An excess of hydrochloric acid is shown by two of them, probably due to free hydrochloric acid contained in the moisture of the sample, and two show appreciable excess of ammonia in a form not yet determined.

In contrast to this simple composition of the primary sublimates is the obvious complexity of the salts that form about some of the vents. These showed a range of color from white through yellow, orange, and bright red, and sometimes pale green. It was apparent, however, that this complexity is due to the action of the primary sublimates and gases upon the rock. In the lower temperature acid fumaroles the rock is altered to a friable brick-red mass saturated with condensed steam. The higher temperature fumaroles show little such alteration, but the associated salts are largely ammonium chloride, free of any iron salts.

Conclusions are as yet tentative. We have not yet studied the fumarolic products of the aqueous condensates or the emanations from the high temperature vents of the hornitos, 500° to 1000°C. One may deduce, however, that the volatiles of the low temperature fumaroles are comparatively simple in composition, consisting essentially of steam, hydrochloric acid, and ammonium chloride, with very minor amounts of H_2S, SO_2, SO_3, and CO_2 in the gases, and NaCl, KCl, and $2\ NH_4F.SiF_4$ in the condensible solids; that the dissociation of NH_4Cl at 250° (this takes place more readily in the presence of steam) causes the change from acid to alkaline nature observed at 240°C in the field; and that the more complex nature of the salts about the vents of the low temperature fumaroles is the result of the action of primary emanations upon the rock.

Further studies on these and the high temperature fumaroles are in progress.

Table 1--Composition of gases, Parícutin Volcano, Michoacan

Designation	Temperature	Reaction	Chloride	Sulfate	Sulfite	Sulfide	Carbonate	Reduction	Odor	Taste	Color of sublimate
	°C										
E	106	Acid	+	+	+	...	+	n. d.	Burnt	Faint saline	White, yellow, orange
C	108	Acid	S	...	...	...	...	n. d.	Hydrochloric	Strong acid	White, yellow, orange
B	116	Acid	S	...	...	...	...	n. d.	Hydrochloric	Strong acid	White, yellow, orange
I	120	Acid	S	...	...	...	...	n. d.	Slight acid	Slight acid	White, orange
F	160	Acid	M	+	+	...	+	n. d.	Hydrochloric	Acid	Yellow, orange
K	179	Acid	S	...	+	...	...	+	None	Acid	White
N	200	Acid	S	...	...	...	...	+	Hydrochloric	Salty acid	White, yellow (Cl?)
A	210	Alkaline	S	...	+	...	...	+	Burnt	Sharp, saline	White (Cl?)
P	240	Acid	S	...	...	...	...	+	Hydrochloric	Acid	White, orange Cl! Pb
S	240	Alkaline	S	+	+	+	+	+	Burnt	Sulfurous	White
G	294	Alkaline	...	+	...	+	+	+	Burnt	Rotten	Gray
J	294	Acid	S	...	+(?)	+	...	+	H_2S slight	Rotten acid	White
H	354	Alkaline	S	...	...	+	...	+	Burnt	Sharp, saline	White
U	370	Alkaline	S	+	+	+	+	+	Burnt	Sulfurous	White
T	400	Alkaline	S	+	+	+	+	+	Burnt	Sulfurous, salty	Sulfur white

Note: S, strong; +, present in small amounts; M, present in moderate amounts; and n. d., not determined.

Table 2--Analyses of four primary sublimates

	1	2	3	4	Remarks
Temperature, °C	120	200	294	352	
NH_3	30.17	30.24	30.65	30.21	
Na	0.39	0.28	0.44	0.32	
K	0.20	0.08	0.26	0.07	
Cl	64.95	62.12	63.22	63.78	
F	0.53	0.76	0.57	0.88	
SiO_2	n. d.	0.12	n. d.	0.69	
R_2O_3	n. d.	0.68	n. d.	0.35	From tube (?)
Reduction	tr.	tr.	tr.	tr.	With $KMnO_4$
X HCl	2.44	....	....	1.24	
X NH_3	....	0.15	1.19	....	
Reaction of gases	acid	acid	alkaline	alkaline	

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NOTES ON FLOW-TIME EFFECTS IN THE GREAT ARTESIAN AQUIFERS OF THE EARTH

P. Wilh. Werner

Abstract--There exist several very large artesian aquifers in the Earth's crust. The Great Australian Artesian Basin [GREGORY, 1906; LOCKHART JACK, 1930; PITMAN and DAVID, 1903; PITMAN, 1908 and 1914] covers an area of nearly 4,000,000 sq km. The groundwater body under the Libyan Desert [BALL, 1927; HELLSTROM, 1940] is estimated to have a length of 1200 km and a width of the same magnitude. In the United States a number of such aquifers have been more or less thoroughly explored, perhaps the most noteworthy being that in the Dakota sandstone [DARTON, 1909; MEINZER and HARD, 1925] with a length and width of some 500 km. An important aquifer lies under the Latvian Devon; only little is known, however, about its actual dimensions.

The aquifers referred to are of great importance for the regions they traverse, as they constitute a vital source of water supply and irrigation. This is especially true as regards the Great Australian Basin, where a large population and huge properties are concerned. Consequently, the flow of the artesian waters has created much interest and has been the subject of investigation by many distinguished authors. It is safe to state, however, that the many interesting and important phenomena encountered in large artesian aquifers are not yet fully elucidated.

The following study aims at throwing some further light upon this problem. It will deal chiefly with the effect of the compressibility of the water and the volume elasticity of the water-conveying medium (aquifer), the latter of which may be referred to as the Meinzer effect [MEINZER and HARD, 1925; THEIS, 1935]. It will be shown that the said agents are essential, first because the volume changes of the water and of the aquifer have a very marked effect upon the flow under variable conditions, that is, when the pressures in the stream are changed in some way or other, and second because the compression represents a storage of considerable magnitude. Also certain physical phenomena in the tapping of water through wells, etc., will be explained by the theory advanced.

The compression theory also possesses a broader geophysical aspect. The dried-out oases in Egypt [HELLSTROM, 1940] may be well explained by such phenomena as will be described in principle in this paper. The same may be true regarding the present-day sterility of old cultivated lands in Turkestan in Asia. With special reference to the Great Australian Basin, the results indicate that it is not out of the way to repeat a warning of dwindling yield, once sounded by J. W. GREGORY [1906], although for another reason than that anticipated by this author in his well-known classical work "The dead heart of Australia."

Introduction

Notation--The following general notation is used throughout this paper:

L = length of the groundwater stream in cm
v = apparent velocity in cm/sec
z = piezometric water level in cm in the aquifer at the point x and the time t
h_0 = original head-water level
σ = pressure in kg/cm^2
t = time in sec
c = coefficient of permeability in Darcy's formula in cm/sec
ϵ = pore space as a decimal fraction
γ = unit weight of the water in kg/cm^3
E_w = modulus of compressibility of the water in kg/cm^2
E_s = modulus of volume elasticity of the aquifer in kg/cm^2
$1/E = [1/E_w + 1/(\epsilon E_s)]$
$k = (cE)/(\gamma \epsilon)$ in cm^2/sec
n = whole numbers 1, 2, 3, etc.

Geological profile--A view of a typical artesian formation is obtained from Figure 1, showing a section of the Dakota groundwater aquifer in the direction of flow, as copied from a paper by N. H. DARTON [1909]. As previously mentioned, the aquifer here consists of sandstone beds, which are covered by thick impermeable shales.

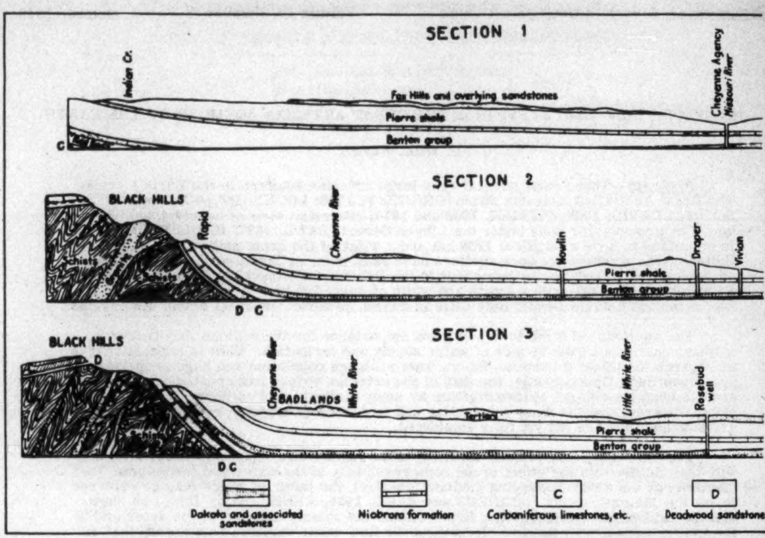

SECTION 1
Indian Cr.
Fox Hills and overlying sandstones
Pierre shale
Benton group
C
Cheyenne Agency
Missouri River
SECTION 2
BLACK HILLS
Schists
Granite
Schists
Rapid
Cheyenne River
Nowlin
Draper
Vivion
Pierre shale
Benton group
D C
SECTION 3
BLACK HILLS
D
Cheyenne River
BADLANDS
White River
Tertiary
Little White River
Rosebud well
Pierre shale
Benton group
D C
Dakota and associated sandstones
Niobrara formation
C
Carboniferous limestones, etc.
D
Deadwood sandstone

Fig. 1 -- Geologic sections across South

Before entering into the theory of our own subject, three features of large artesian aquifers are worth noticing. As may be gathered from Figure 1, these features are: (1) The length is so extensive in relation to the variations in altitude that the aquifer may be considered as horizontal; (2) the thickness of the aquifer is so small as compared with the length that the groundwater flow may be assumed one- or two-dimensional even under variable conditions; and (3) the slope of the piezometric water level in its natural state is very small.

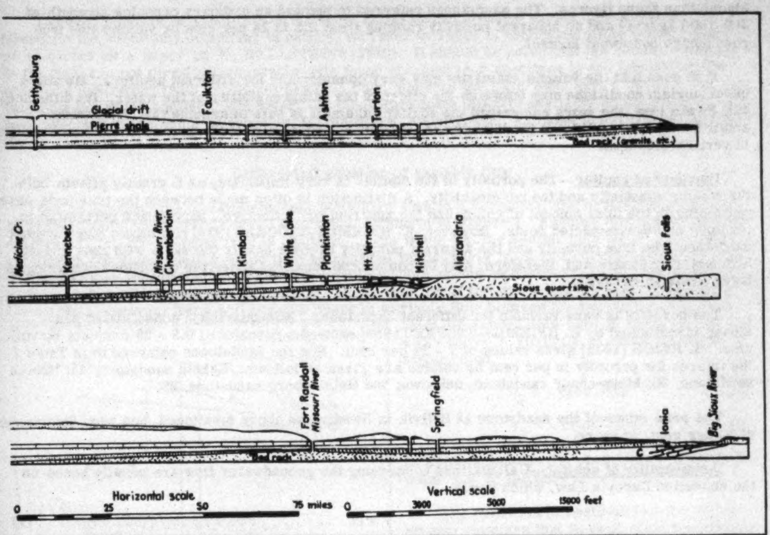
Due to the flat gradient, the natural discharge of an artesian groundwater stream is comparatively small. For instance, the total discharge of the Dakota groundwater stream, before any water was tapped by wells, was estimated at some 0.0006 m^3/sec per km width of the aquifer.

Factors governing the flow--As will be shown in the following, by equations (4), (5), and (6), the main factors governing the variable artesian flow are as follows: (1) Unit weight of water; (2) compressibility of water; (3) volume elasticity of aquifer; (4) porosity of aquifer; (5) permeability of aquifer.

Of these factors the unit weight and the compressibility of the water are easily determined, whereas the factors pertaining to the aquifer are of a rather complex nature, interdependent and very variable. It may be premised that for the purpose of the present investigation all the governing factors will be assumed constant for any given aquifer, at least within intervals. This, of course, involves certain rather rough approximations in several cases, but the inaccuracy will not interfere in principle with the validity of the results obtained.

Unit weight of water--The unit weight of fresh water may be taken at 0.001 kg/cm^3. The weight varies with the salinity. For instance, at Höllvik in southern Sweden, two deep borings have recently been sunk to an artesian aquifer (sandstone) located some 1200 m under the level of the Baltic Sea and containing salt water with a density of about 0.001085 kg/cm^3.

Compressibility of water--The modulus of compressibility of water is a well-known physical quantity. It is practically constant and may be taken at about E_w = 21,000 kg/cm^2. In view of this


Gettysburg
Glacial drift
Pierre shale
Faulkton
Ashton
Turton
Bed rock (granite, etc.)
Medicine Cr.
Kennebec
Missouri River
Chamberlain
Kimball
White Lake
Plankinton
Mt. Vernon
Mitchell
Alexandria
Sioux Falls
Sioux quartzite
Fort Randall
Missouri River
Springfield
Ionia
Big Sioux River
C
Horizontal scale
0
25
50
75 miles
Vertical scale
0
3000
5000
15000 feet

Dakota (according to N. H. DARTON)

value the common assumption that water be considered as an incompressible fluid, constitutes a sufficiently close approximation in many cases of groundwater flow. It may usually be applied even to variable conditions, if the aquifer is of moderate size. But for large artesian aquifers it is necessary, in case of variable conditions, to take into consideration the compressibility of the water.

Volume elasticity of aquifer--When the aquifer, under variable-flow conditions, is subjected to some variation in load, a change in its volume will occur, partly due to the elasticity of the solid constituents of the aquifer and partly due to a change in the pore space. According to the terminology used by L. H. ADAMS and E. D. WILLIAMSON [1923], the two types of elasticity may be referred to as "inner" and "outer" compressibility, respectively. For compacted sands and sandstones the inner compressibility is generally so small that it may be neglected in comparison with the outer compressibility. Therefore, the volume elasticity of the aquifer, in the meaning of the present paper, is represented by an equivalent modulus of elasticity E_s, pertaining to a change of the porosity, and more specifically applying to the case of no lateral displacement of the material.

According to K. v. TERZAGHI [1925] the value of E_s for sands heavily compacted in the laboratory from the state of a loose fill is directly proportional to the superimposed load. For river sand with sharp corners he gives the value $E_s = 176\sigma$, in which σ denotes the pressure; if, for instance, $\sigma = 200$ kg/cm^2 we have $E_s = 35{,}200$ kg/cm^2. This value checks rather well with tests executed by A. F. SAMSIOE of VBB (data not published). At this pressure, however, the sand has a very small porosity, amounting to some few per cent.

As demonstrated by F. BREYER [1939], K. JOCHMUS-STÖCKE [1939], H. REICH [1933], and others, the volume elasticity of sandstones is also influenced by the compaction. It is further highly affected by the porosity and the consolidation, which in turn depend on the rock pressure and the diagenetic processes to which the aquifer has been subjected in the course of geological ages.

According to K. JOCHMUS-STÖCKE [1939] the ordinary Young's modulus of elasticity of a number of investigated non-quartzitic consolidated sandstones varied between 50,000 and 300,000 kg/cm^2. Evidently the modulus of volume elasticity E_s, with no lateral displacement, must be

higher than these figures. The sandstones referred to showed an ordinary crushing strength of 300-1800 kg/cm^2 and an apparent porosity ranging from 0.5 to 24 per cent by volume (the true pore space somewhat larger).

It is seen that the volume elasticity may vary considerably for different aquifers. Its effect under certain conditions may outweigh the effect of the compressibility of the water. Its influence will be the less, the more compacted the aquifer is, and it is safe to assume that it is rather small for well-consolidated sandstones and limestones, especially if the ground water flows chiefly in vertical fissures.

Porosity of aquifer--The porosity of the aquifer is very important, as it greatly affects both the volume elasticity and the permeability. A distinction is often made between the true pore space pertaining to the total amount of voids, and the apparent or "effective" pore space pertaining to the open or interconnected voids. However, K. JOCHMUS-STÖCKE [1939] has shown that for most sandstones the true porosity and the apparent porosity become nearly the same with time and at high water pressure and, therefore, may be considered identical under the conditions occurring in large artesian aquifers.

The porosity is very variable for different sandstones. Non-quartzitic consolidated sandstones investigated by K. JOCHMUS-STÖCKE [1939] showed a porosity of 0.5 - 25 per cent by volume. H. REICH [1933] gives values of 7 - 34 per cent. For the sandstones referred to in Table 1 the figures for porosity in per cent by volume are given as follows: Dakota sandstone, 43; Nubian sandstone, 30; Mingechaur sandstone, unknown; and Helsingborg sandstone, 25.

The pore space of the sandstone at Höllvik in Sweden, as above mentioned, has been determined at 30 per cent, or more.

Permeability of aquifer--Calculations concerning the groundwater flow are usually based on the so-called Darcy's Law, which reads

$$v = cI \qquad (1)$$

where I = hydraulic gradient, and other symbols are as listed under "Notations" above.

Through careful tests by several investigators [DACHLER, 1936] it has been ascertained that Darcy's Law is at least nearly true for a very wide range of conditions. It is now generally conceded that it may be applied with sufficient accuracy to most practical cases of groundwater flow in sands and sandstones, which constitute the most important aquifers in nature. Equation (1) will therefore be applied throughout in the following investigation, the more so as other uncertainties in groundwater calculations make the use of more complicated formulas unwarranted.

Table 1--Values of c after B. HELLSTROM [1940]

Material	Approximate values permeability factor c in equation (1)
	cm/sec
Dakota sandstone (U. S. A.)	3×10^{-3} to 4×10^{-3}
Nubian sandstone (Libyan Desert)	
(a) Laboratory tests on solid specimen without fissures	7.7×10^{-3}
(b) Estimated for the Dakhla Oasis	2.4×10^{-3} to 2.4×10^{-2}
Sandstone at Mingechaur (Trans-Caucasia)	
(a) Estimated from observations in wells	7×10^{-5} to 1×10^{-3}
(b) Laboratory tests on solid specimen without fissures	8×10^{-6}
Sandstone and slate at Helsingborg (Sweden)	
(a) Flow in horizontal direction estimated from observations in a mine	4×10^{-5}
(b) Laboratory tests on solid specimen of sandstone without fissures	1.4×10^{-3}

The coefficient of permeability of different sands and sandstones varies considerably. To illustrate the conditions occurring in nature, we refer to Table 1, containing some actual values of c, quoted in a paper by B. HELLSTROM [1940]. It should be noted that the results obtained in the field are not directly comparable with those obtained on a specimen in the laboratory, because the laboratory tests represent samples only, whereas the field tests give a certain average value for the whole aquifer. Moreover, the laboratory tests hitherto available do not seem to have been executed at the same compaction, temperature, salinity, etc., as those prevailing in the aquifer.

Differential equation of variable flow

Let us consider the two-dimensional stationary flow in a horizontal and homogeneous aquifer of uniform and comparatively small thickness, as shown in Figure 2. Assume that some boundary condition of the groundwater flow is changed. If the water and the aquifer kept their volumes, the velocity in the whole aquifer would then be changed immediately from that corresponding to the original to that corresponding to the new condition, both values independent of time and in accordance with Darcy's Formula. Due to the compressibility of the water and the volume elasticity of the aquifer, however, there will occur a phase of variable flow between the two states of equilibrium. Although this flow is variable, one may apply Darcy's Formula to small elements of length, thus

$$v_x = -c(\partial z/\partial x) \quad \text{(2a)}$$

$$v_y = -c(\partial z/\partial y) \quad \text{(2b)}$$

in which z denotes the piezometric level in the point x,y at the time t.

The condition of continuity of the water stream requires that in each point the storage due to compression per unit time equals the change in flow per unit length. Neglecting small terms of the second order, we obtain

$$(\partial v_x/\partial x) + (\partial v_y/\partial y) = -(\gamma\epsilon/E)(\partial z/\partial t) \quad \text{(3)}$$

$$(1/E) = (1/E_w) + (1/\epsilon E_s) \quad \text{(4)}$$

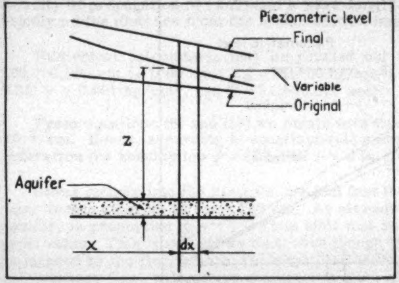


Fig. 2--Flow in horizontal and homogeneous aquifer of uniform and comparatively small thickness

Equation (4) implies that the time effect due to the compressibility of the water and that due to volume elasticity of the aquifer are additive. In this connection, however, it is worth noticing that it is inconceivable that the thick strata overlying the aquifer are flexible enough to follow a local "cone of depression" such as, for instance, occurs during the first period of pumping through a single well. In such cases the time effect is caused solely by the compressibility of the water, and the time effect due to the volume elasticity sets in only after the cone of depression has extended over a larger area. It is necessary to keep this in mind in the practical application of the theory.

As stated in the introduction, the values of γ, E, ϵ, and c may be assumed constant for a given aquifer. Combining equations (2) and (3), we then obtain after some transformations

$$(\partial^2 z/\partial x^2) + (\partial^2 z/\partial y^2) = (1/k)(\partial z/\partial t) \quad \text{(5)}$$

in which

$$k = cE/\gamma\epsilon \quad \text{(6)}$$

It should be noted that the quantity k has the same dimension as the so-called kinematic viscosity [LAMB, 1932], namely, cm^2/sec in the measuring system used. It is suggested, therefore, to call k the viscosity factor of the aquifer.

With the assumptions stated above, equation (5) constitutes the general differential equation for the piezometric level under variable flow due to the compressibility of the water and the volume elasticity of the aquifer. It is identical with the well-known differential equation for the flow of heat in solids and can be integrated under various conditions [CARSLAW, 1921; LAMB, 1932]. In the following the solution will be given for a few of the most important typical cases. We will refer chiefly to one-dimensional flow, for which equation (6) reads

$$(\partial^2 z/\partial x^2) = (1/k)(\partial z/\partial t) \ldots\ldots (7a)$$

In some cases it is convenient to use polar coordinates, whereby equation (6) takes the form

$$(\partial^2 z/\partial r^2) + (1/r)(\partial z/\partial r) + (1/r^2)(\partial^2 z/\partial \phi^2) = (1/k)(\partial z/\partial t) \ldots\ldots (7b)$$

Assuming full symmetry, equation (7b) is reduced to

$$(\partial^2 z/\partial r^2) + (1/r)(\partial z/\partial r) = (1/k)(\partial z/\partial t) \ldots\ldots (7c)$$

which will be used in the following for the investigation of the effect of pumping through a single well, involving two-dimensional flow.

General applications

To make the matter perspicuous and apt to mathematical treatment, we may consider the simple case demonstrated in Figure 3, representing an artesian groundwater stream in a horizontal and homogeneous aquifer of uniform and comparatively small thickness.

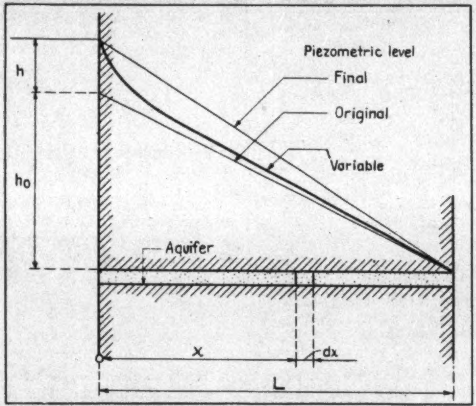


Fig. 3 -- Artesian ground water stream in horizontal and homogeneous aquifer of uniform and comparatively small thickness

(1) Fluctuations in head-water pressure--The first question that arises concerns the manner in which fluctuations in the head-water pressure are transmitted through the groundwater stream. Such fluctuations may be caused, for instance, by seasonal variations in the rainfall on the intake beds. For the purpose of the investigation the fluctuations may be given by the periodic function.

$$h = q \sin \delta t \ldots\ldots (8)$$

in which q = amplitude of fluctuations, T = period of fluctuations, and $\delta = 2\pi/T$.

The solution of the problem is as in equation (9).

$$z = h_0(1 - \xi) + q/\sin(\varphi + \psi)[e^{\beta x}\sin\varphi \,\sin(\delta t + \beta x + \psi) + e^{-\beta x}\sin\psi \,\sin(\delta t - \beta x - \varphi)] \,.\, (9)$$

in which

$$\beta = (\delta/2k)^{1/2} \ldots\ldots (10)$$

$$\tan\psi = \sin 2\beta L/e^{-2\beta L} - \cos 2\beta L \ldots\ldots (11)$$

$$\varphi = -(\psi + 2\beta L) \quad \text{(12)}$$

and $\xi = (x/L)$.

Through substitution it is verified that the expression (9) satisfies equation (7a) as well as the boundary conditions

$$z = h_0 + q \sin \delta t \text{ for } x = 0 \quad \text{(13a)}$$

$$z = 0 \text{ for } x = L. \quad \text{(13b)}$$

Since in our case we consider only groundwater streams of very great length, we obtain approximately $\psi = -2\beta L$ and $\varphi = 0$. Thus, according to equation (9),

$$z = h_0(1 - \xi) + [qe^{-\beta x}\sin(\delta t - \beta x)] \quad \text{(14)}$$

From equation (14) several conclusions may be drawn. It is seen that the periodic fluctuations in the head-water pressure are transmitted through the groundwater stream as oscillations with a velocity of propagation of (δ/β) and a wave length of $\lambda = 2\pi/\beta$. The amplitude decreases very rapidly as the distance from the intake section increases.

Numerical calculations may be carried out for the following values as Example 1: L = 100,000,000 cm (= 1000 km); E_w = 21,000 kg/cm^2; E_s = 100,000 kg/cm^2; $c = 4 \times 10^{-2}$ cm/sec; ϵ = 0.20; γ = 0.001 kg/cm^3; and T = 31,500,000 sec (= 1 year).

From equations (6) and (10) we obtain with these values $k = 2.05 \times 10^6$ cm^2/sec and $\beta \sim 2.22 \times 10^{-7}$/cm. Hence, according to equations (11) and (12), there is no doubt that in the case under consideration the assumption $\psi = 2\beta L$ and $\phi = 0$ is a very close approximation.

Going further into the example, we find that the velocity of propagation is about 0.9 cm/sec. The wave length amounts to some 280 km. As already indicated the amplitude decreases very rapidly, namely, in proportion to $e^{-2\pi}$. Thus after one oscillation it becomes only about 1/535 of its original value. This result shows that, even though the portion near the intake section is markedly influenced by the fluctuations, the main part of large artesian aquifers, having once reached a state of stationary flow, will always remain in a state of relative hydrodynamic equilibrium when they are undisturbed by such outside influences as, for instance, pumping through wells.

(2) Sudden rising of head-water pressure--An important problem is to investigate the effect of raising the head-water level permanently. A practical aspect of this problem is obtained, for instance, by considering the suggestion recently made [HELLSTROM, 1940] to lift the piezometric groundwater level in certain parts of the Libyan Desert by raising the Aswan Dam on the Nile. The case is also interesting, inasmuch as it most clearly shows the general nature of the time effects considered.

Let us again turn to the one-dimensional groundwater stream in Figure 3. If the head-water level be suddenly increased from h_0 to $(h_0 + h)$, we may write

$$z = h_0(1 - \xi) + h\left[(1 - \xi) - (2/\pi)\sum_{n=1}^{\infty}(1/n)e^{-\alpha t}\sin n\pi\xi\right] \quad \text{(15)}$$

where

$$\alpha = n^2(\pi^2/L^2)k \quad \text{(16)}$$

Through substitution it is verified that the expression (15) satisfies the differential equation (7a) as well as the initial and boundary conditions applying to the case, viz.,

$$z = h_0(1 - \xi) \text{ for } t = 0. \quad \text{(17a)}$$

$$z = h_0 + h \text{ for } x = 0 \quad \text{(17b)}$$

$$z = 0 \text{ for } x = L \quad \text{(17c)}$$

Equation (15) thus constitutes the solution of the problem put forward. It is seen that, theoretically, the new state of equilibrium, corresponding to the increased water pressure, will be established only after infinite time, because

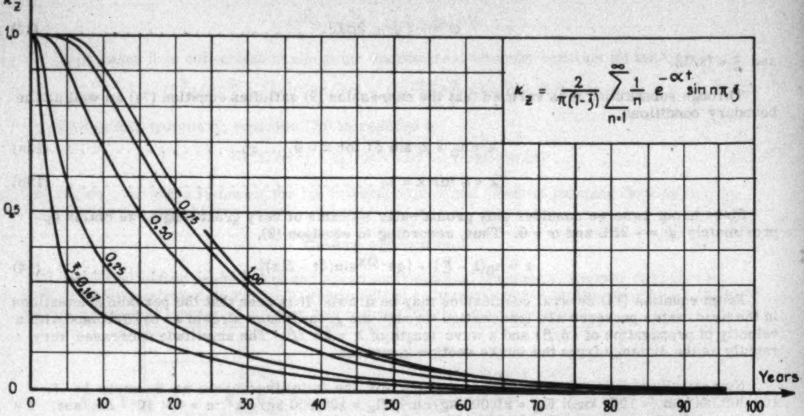


Fig. 4 -- Pressure-time effect due to sudden increase in head-water level in artesian aquifer with length of 1000 km and viscosity factor $k = 2.05 \times 10^6$ cm^2/sec

$$z = (h_0 + h)(1 - \xi) \text{ for } t = \infty \quad \text{(17d)}$$

The time effect due to compression is given by the expression

$$\delta_z = \kappa_z \, h(1 - \xi) \quad \text{(18)}$$

in which

$$\kappa_z = [2/\pi\,(1 - \xi)] \sum_{n=1}^{\infty} (1/n)\, e^{-\alpha t} \sin n\pi\xi \quad \text{(19)}$$

According to equations (2) and (15) the variable velocity becomes

$$v = (c/L)[h_0 + h(1 + 2 \sum_{n=1}^{\infty} e^{-\alpha t} \cos n\pi\xi)] \quad \text{(20)}$$

and thus the corresponding time effect due to compression

$$\delta_v = \kappa_v \, c(h/L) \quad \text{(21)}$$

in which

$$\kappa_v = 2 \sum_{n=1}^{\infty} e^{-\alpha t} \cos n\pi\xi \quad \text{(22)}$$

For numerical calculations, as Example 2, we assume the same values as in Example 1. With these values the equations (19) and (22) are evaluated in Figures 4 and 5.

Figure 4 shows the pressure-time effect as function of time. Taking, for instance, $\xi = 0.5$, that is, a point halfway between the intake and the outlet of the groundwater stream, the increase in pressure due to the raised head-water level obtains 50 per cent of its full value after some 15 years and practically reaches its full value after some 75 years. Even for $\xi = 0.167$ the corresponding figures will be as high as some three and 50 years, respectively. All these figures refer to $c = 4 \times 10^{-2}$ cm sec. Observing the fact that the time effect is principally determined by the expression

$$\alpha = n^2(\pi^2/L^2)k \quad \text{(16)}$$

it is seen that for the same time effect the time varies inversely with c. Hence, for $c = 4 \times 10^{-3}$ cm/sec the above figures will be ten times higher, for example, for $\xi = 0.5$ no less than 150 and 750 years, respectively. Referring to Table 1 it may also be seen that the examples shown by no means exaggerate the conditions met with in nature.

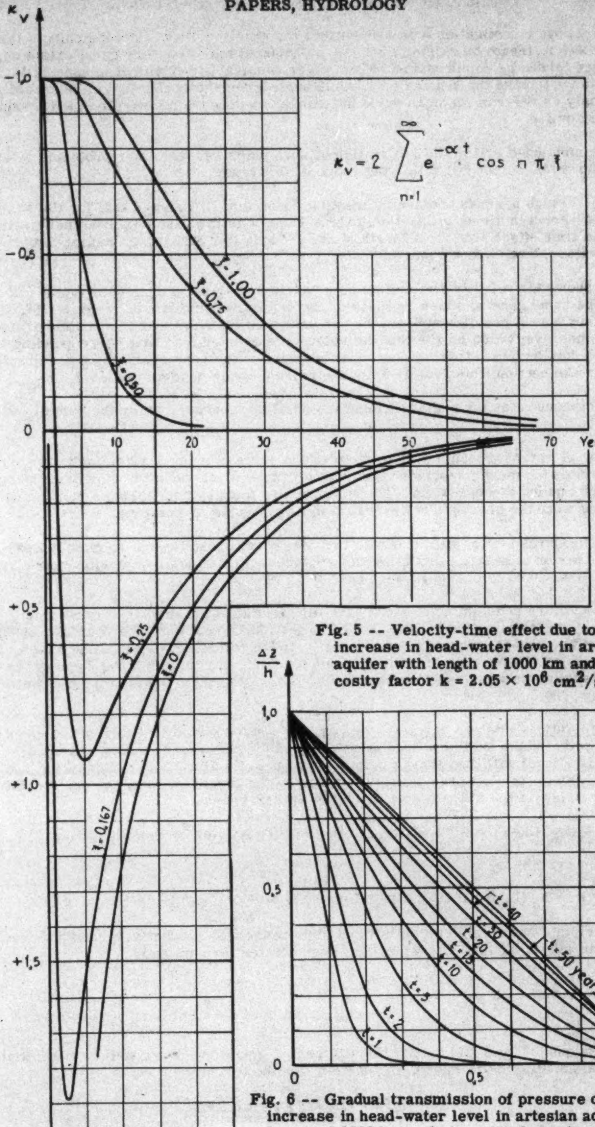


Fig. 5 -- Velocity-time effect due to sudden increase in head-water level in artesian aquifer with length of 1000 km and viscosity factor $k = 2.05 \times 10^6$ cm^2/sec

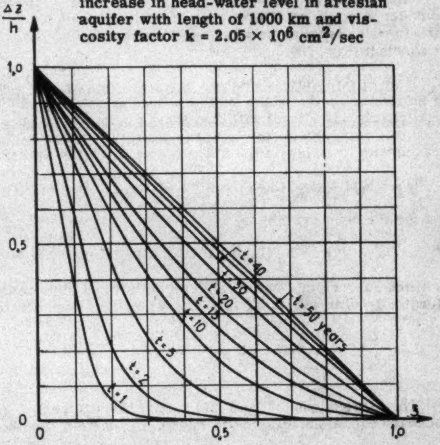


Fig. 6 -- Gradual transmission of pressure due to sudden increase in head-water level in artesian aquifer with length of 1000 km and viscosity factor $k = 2.05 \times 10^6$ cm^2/sec

From the above investigation it is evident that the practicability of replenishing a large artesian groundwater stream by raising the head-water level may to a very great extent depend on the time effect caused by compression. From an economical standpoint it is especially of paramount importance to base the scheme on a safe knowledge of the coefficient of permeability in the aquifer, not only as regards its mean value but also as to its possible variation from section to section of the aquifer.

It may be mentioned that in the realization of such plans several other problems would be met with, which, however, do not fall within the scope of this study.

Equation (16) also permits another interesting deduction. It is noted that for the same time effect the time varies in direct proportion to L^2. Thus, with the c-values used there will be quite an appreciable time effect even for a length of the groundwater stream amounting to only 1/1000 of the above values, that is, $L = 1$ km.

Figure 5 shows the velocity-time effect as a function of time. For greater values of ξ the curves have the same general shape as those of the pressure-time effect. For smaller values of ξ, however, they have a peculiar appearance, inasmuch as the time effect in a comparatively short time becomes positive, which means that the velocity is greater than that corresponding to the ultimate state of equilibrium. This, of course, is because of the very sharp pressure gradient existing near the intake section immediately after the raising of the head-water level.

Figure 6 demonstrates the gradual transmission of the pressure along the path of the groundwater stream.

(3) Tapping of water through a slit--In view of the value of ground water for water supply and irrigation, perhaps the most important case from a practical standpoint occurs when water is being tapped from the aquifer through wells. The compression thereby represents a storage which becomes released when the pressure is decreased by overflowing or pumping.

The following investigation will deal with the case when the wells are so closely spaced that their hydraulic action is nearly equal to that of a narrow slit in accordance with Figure 7. As before, the flow is assumed to be one-dimensional.

The solution of the problem must satisfy the differential equation (7a). Concerning the boundary conditions, special attention must be called to the intake section. The boundary conditions here may depend on several factors (storage, etc.). In the following, two limiting cases will be considered, namely: (1) The rate of infiltration is constant, implying that the slope of the piezometric water level at the intake section remains constant (Fig. 7A); and (2) the head-water level is constant (Fig. 7B).

Rate of infiltration-constant; instantaneous draw-down--Assume now that with a constant rate of infiltration in the intake section a sudden lowering of the water level in the slit occurs. The piezometric water level will then show a point of discontinuity at the slit. Introducing two systems of coordinates, one for the left branch with its origin in the intake section, and one for the right branch with its origin in the slit, we may write for the left branch

$$z_\ell = h_0[1 - (L_\ell/L)\xi_\ell] - h\left\{1 - (4/\pi)\sum_{n=0}^{\infty}[(-1)^n/(2n+1)]e^{-\alpha_\ell t}\cos(2n+1)(\pi/2)\xi_\ell\right\} \quad . . (23)$$

and for the right branch

$$z_r = h_0\,(L_r/L)(1 - \xi_r) - h[(1 - \xi_r) - (2/\pi)\sum_{n=1}^{\infty}(1/n)\,e^{-\alpha_r t}\sin n\pi\xi_r] \quad . . . . . (24)$$

in which subscripts ℓ and r refer to the left and right branches, respectively, and h = draw-down of water level in slit, $L = (L_\ell + L_r)$ = length of groundwater stream, and

$$\alpha_\ell = (2n+1)^2(\pi^2/4L_\ell^2)k \quad . . . . (25)$$

$$\alpha_r = n^2\,(\pi^2/L_r^2)k \quad . . . . (26)$$

The expressions (23) and (24) satisfy the differential equation (7a) as well as the initial and boundary conditions applying to Figure 7A, namely, for the left branch

$$z_\ell = h_0\,[1 - (L_\ell/L)\xi_\ell] \text{ for } t = 0 \quad . . . . (27a)$$

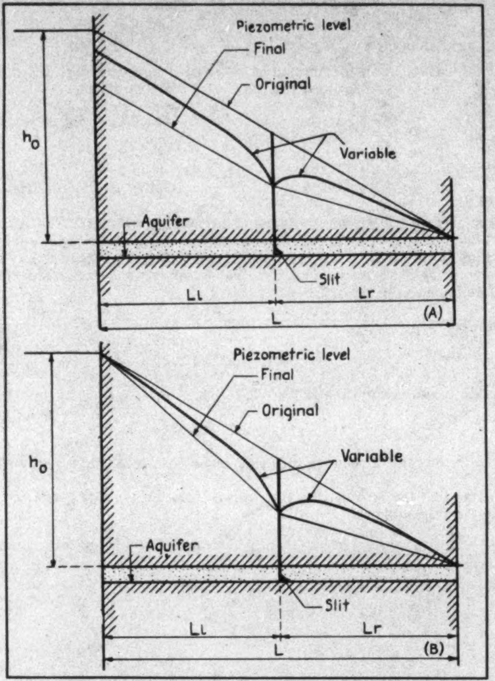

Piezometric level
Final
Original
Variable
h_0
Aquifer
Slit
Ll
Lr
L
(A)
Piezometric level
Final
Original
Variable
h_0
Aquifer
Slit
Ll
Lr
L
(B)

Fig. 7--Wells so closely spaced that hydraulic action is nearly equal that of a narrow slit: (A) Constant infiltration; (B) constant head-water level

$$z_\ell = h_0 (L_r/L) - h \text{ for } x = L_\ell \qquad (27b)$$

$$(\partial z_\ell / \partial x) = -(h_0/L) \text{ for } x = 0 \qquad (27c)$$

and for the right branch

$$z_r = h_0 (L_r/L)(1 - \xi_r) \text{ for } t = 0 \qquad (28a)$$

$$z_r = h_0 (L_r/L) - h \text{ for } x = 0 \qquad (28b)$$

$$z_r = 0 \text{ for } x = L_r \qquad (28c)$$

Equations (23) and (24) constitute the solution of the problem. The new state of equilibrium theoretically occurs only after infinite time and is described by the equations

$$z_\ell = h_0 [1 - (L_\ell/L)\xi_\ell] - h \text{ for } t = \infty \qquad (29)$$

$$z_r = [h_0 (L_r/L) - h](1 - \xi_r) \text{ for } t = \infty \qquad (30)$$

which, if the water level in the slit be drawn down to the aquifer (assuming an adequate pumping equipment feasible), read

$$z_\ell = h_0[(L_\ell/L)(1 - \xi_\ell)] \text{ for } t = \infty \tag{31}$$

$$z_r = 0 \text{ for } t = \infty \tag{32}$$

It is of great interest to know the amount of water discharged through the slit. If Q denotes this discharge, and A the cross-sectional area of the aquifer, we have

$$Q = -\,cA[(\partial z_\ell/\partial x)|_{x = L_\ell} - (\partial z_r/\partial x)|_{x = 0}] \tag{33}$$

from which

$$Q = cA(h/L_r)[1 + 2(L_r/L_\ell) \sum_{n=0}^{\infty} e^{-\alpha_\ell t} + 2 \sum_{n=1}^{\infty} e^{-\alpha_r t}] \tag{34}$$

For t = 0 the discharge becomes very large (theoretically infinite). The same condition also occurs in a single well and gives a full explanation of the phenomenon observed in boreholes, namely, that the yield in the first instance after the borehole has reached the artesian aquifer shows rather an explosive character. As far as the writer can see, this phenomenon can be explained only by the compressibility of the water.

For $t = \infty$ we receive

$$Q = cA(h/L_r) \tag{35}$$

which for a complete draw-down in the slit reads

$$Q_c = cA(h_0/L) \tag{35a}$$

thus corresponding to the total discharge of the groundwater stream in its natural condition.

It should be noted that the amount of water drawn from the storage represented by compressed water is given by the expression

$$\Delta Q = 2cA(h/L_r)[(L_r/L_\ell) \sum_{n=0}^{\infty} e^{-\alpha_\ell t} + \sum_{n=1}^{\infty} e^{-\alpha_r t}] \tag{36}$$

The total amount of water obtainable from the storage is

$$M = \int_0^\infty \Delta Q dt \tag{37}$$

or

$$M = m(\gamma \epsilon /E)AhL \tag{38}$$

in which

$$m = (2/\pi^2) \left\{(L_\ell/L) \sum_{n=0}^{\infty} [4/(2n + 1)^2] + (L_r/L) \sum_{n=1}^{\infty} (1/n^2)\right\} = 1 - (2/3)(L_r/L) \tag{39}$$

For a complete draw-down in the slit we obtain

$$M_c = m(\gamma \epsilon /E)Ah_0L_r \tag{38a}$$

If the total amount of storage available be uniformly distributed, it would represent a yield equal to the natural discharge of the groundwater stream for a continuous period of

$$T = (m/k)(h/h_0)L^2 \tag{40}$$

and

$$T_c = (m/k)L_rL \tag{40a}$$

For numerical calculations we assume the following values as Example 3: L = 50,000,000 cm (= 500 km); $L_\ell = L_r = 0.5L$; $E_w = 21{,}000$ kg/cm²; $E_s = 100{,}000$ kg/cm², and $E_s = \infty$, respectively; $c = 2 \times 10^{-3}$ cm/sec; $\epsilon = 0.16$; and $\gamma = 0.001$ kg/cm³.

With these values we obtain $k = 1.26 \times 10^5$ cm²/sec, and $k = 2.62 \times 10^5$ cm²/sec for $E_s = 100{,}000$ and $E_s = \infty$, respectively. According to equation (39) m = (2/3), and thus according to equation

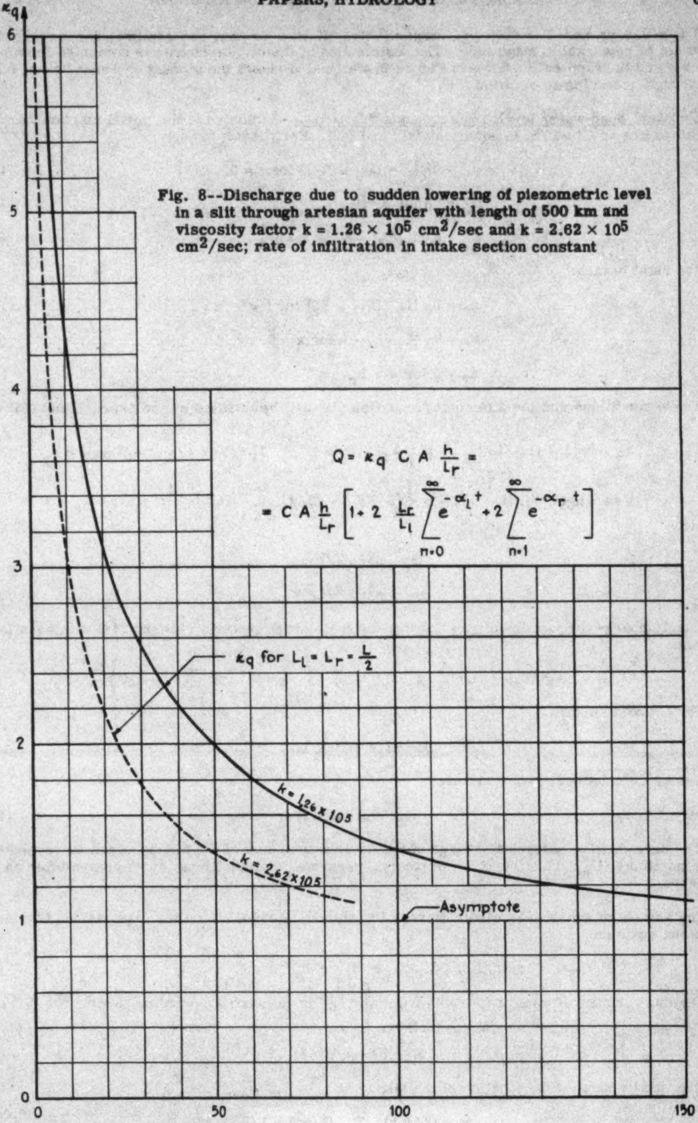


Fig. 8--Discharge due to sudden lowering of piezometric level in a slit through artesian aquifer with length of 500 km and viscosity factor $k = 1.26 \times 10^5$ cm^2/sec and $k = 2.62 \times 10^5$ cm^2/sec; rate of infiltration in intake section constant

(40a) $T_c \sim 210$ yr and $T_c \sim 100$ yr, respectively. It is seen that the compression represents a storage of remarkable magnitude. The distribution of the slit discharge is computed from equation (34) and is graphically shown in Figure 8, which also shows the amount of water drawn from the storage according to equation (36).

Constant head-water level; instantaneous draw-down--In this case the initial and boundary-conditions are as (Fig. 7B) in equations (41) and (42). For the left branch

$$z_\ell = h_0 [1 - (L_\ell/L)\xi_\ell] \text{ for } t = 0 \qquad (41a)$$

$$z_\ell = h_0 \text{ for } x = 0 \qquad (41b)$$

$$z_\ell = h_0(L_r/L) - h \text{ for } x = L_\ell \qquad (41c)$$

For the right branch

$$z_r = h_0 (L_r/L)(1 - \xi_r) \text{ for } t = 0 \qquad (42a)$$

$$z_r = h_0 (L_r/L) - h \text{ for } x = 0 \qquad (42b)$$

$$z_y = 0 \text{ for } x = L_r \qquad (42c)$$

These conditions and the differential equation (7a) will be fulfilled by the expressions (43) and (44)

$$z_\ell = h_0[1 - (L_\ell/L)\xi_\ell] - h \left\{ \xi_\ell - (2/\pi) \sum_{n=1}^{\infty} [(-1)^{n-1}/n] e^{-\alpha_\ell t} \sin n\pi\xi_\ell \right\} \qquad (43)$$

$$z_r = h_0(L_r/L)(1 - \xi_r) - h \left\{ (1 - \xi_r) - (2/\pi) \sum_{n=1}^{\infty} (1/n) e^{-\alpha_r t} \sin n\pi\xi_r \right\} \qquad (44)$$

in which

$$\alpha_\ell = n^2(\pi^2/L_\ell^2)k \qquad (45)$$

$$\alpha_r = n^2(\pi^2/L_r^2)k \qquad (46)$$

The discharge through the slit is obtained by combining equations (43) and (44) with equation (33), thus

$$Q = cA(h/L_r) \left\{ (L/L_\ell) + 2(L_r/L_\ell) \sum_{n=1}^{\infty} e^{-\alpha_\ell t} + 2 \sum_{n=1}^{\infty} e^{-\alpha_r t} \right\} \qquad (47)$$

For $t = \infty$ we obtain

$$Q = cA(h/L_r)(L/L_\ell) \qquad (48)$$

which for a complete draw-down reads

$$Q_c = cA(h_0/L_\ell) \qquad (48a)$$

It is seen that the natural discharge of the aquifer upstream of the slit becomes increased in the proportion L/L_ℓ. This increase, of course, presumes that additional water is available on th intake beds.

The amount of water drawn from storage is obtained by substituting the expressions (45) and (46) in the equation

$$\Delta Q = 2cA(h/L_r) \left\{ (L_r/L_\ell) \sum_{n=1}^{\infty} e^{-\alpha_\ell t} + \sum_{n=1}^{\infty} e^{-\alpha_r t} \right\} \qquad (49)$$

The total amount of water obtainable from storage is calculated according to equation (37) and becomes

$$M = m(\gamma\epsilon/E)AhL \qquad (50)$$

in which, independent of the location of the slit

$$m = (2/\pi^2) \sum_{n=1}^{\infty} (1/n^2) = 1/3 \qquad (51)$$

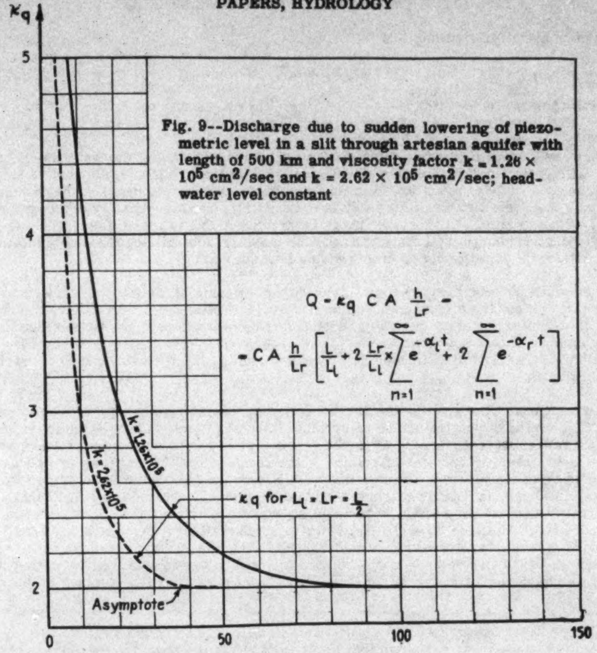


Fig. 9--Discharge due to sudden lowering of piezometric level in a slit through artesian aquifer with length of 500 km and viscosity factor k = 1.26 × 10^5 cm^2/sec and k = 2.62 × 10^5 cm^2/sec; headwater level constant

For a complete draw-down in the slit we receive

$$M_c = (1/3)(\gamma \epsilon /E)Ah_0L_r \dots\dots\dots\dots \text{(50a)}$$

For the times T and T_c we obtain

$$T = (1/3k)(h/h_0)L^2 \dots\dots\dots\dots \text{(52)}$$

and

$$T_c = (1/3k)L_rL \dots\dots\dots\dots \text{(52a)}$$

Numerical calculations, Example 4, may be carried out with the values used in Example 3. With these values equation (52a) gives $T_c \sim 105$ yr and $T_c \sim 50$ yr, respectively. The distribution of the slit discharge is computed from equation (47), and is graphically shown in Figure 9, which also shows the amount of water drawn from storage according to equation (49).

It is worth observing that the total amount of water pumped from storage according to equations (38) and (50) is not equal to the amount of water released. This latter quantity is represented by the expression

$$M_r = m_r(\gamma \epsilon /E)AhL \dots\dots\dots\dots \text{(53)}$$

in which

$$m_r = 1 - (1/2)(L_r/L) \dots\dots\dots\dots \text{(54)}$$

for the case of constant infiltration, and

$$m_r = 1/2 \quad \ldots\ldots \quad (55)$$

for the case of constant head-water level. The "loss" of released water is discharged through the outlet section of the aquifer.

From Figures 8 and 9 it is evident that an instantaneous lowering of the water level in the slit results in a rather uneven distribution of the discharge with time. This result implies that if the wells of a large well district are allowed to flow freely, or are pumped heavily, the discharge of the district may for some time be very much in excess of the natural capacity of the groundwater stream. The excess water, of course, is drawn from storage due to compression. It may be concluded that the discharge of a well district cannot be used for determining the safe yield of the district without taking the storage due to compression into account.

In the successive development of a well district the lowering of the water level will occur more or less gradually. Also, from a practical point of view, it is often desirable to have the discharge more evenly distributed. It may, therefore, sometimes be of interest to investigate the case when the pressure in the slit is a function of time. This case may be studied by means of Duhamel's theorem [CARSLAW, 1921] for the conduction of heat in solids, but will not be incorporated in the present investigation.

The numerical examples given in the foregoing have been carried through with constant values of the diffusivity during the entire period of variable flow. As pointed out in the introduction, however, the Meinzer effect sets in only after the depression of the piezometric level has extended over a larger area, whereas the time effect due to the compressibility of the water will always be prevalent and of an easily determined magnitude. In Examples 3 and 4 the latter time effect for the discharge has also been calculated separately and plotted with dashed lines in Figures 8 and 9. It is evident that the actual time effect in the aquifer would constitute a transition between the dashed and solid lines in these figures. This fact is worth noticing. By comparing actual discharges (or falling water levels) over a considerable period with the corresponding time effect due to the compressibility of the water it might be possible in this way to obtain a conception of the magnitude of the Meinzer effect or at least to obtain a check of the value arrived at by other methods.

(4) Tapping of water through a single well--The capacity of any single well, or even a small group of wells, is generally so moderate that it does not affect the boundary conditions of a large aquifer for an extraordinarily long time. Consequently, this case may be studied under the assumption that the aquifer is infinite and the original piezometric surface horizontal. For the purpose of the investigation the well may be replaced by a line source [CARSLAW, 1921] coinciding with the z-axis.

Using polar coordinates and assuming full symmetry, the differential equation (7c) may be applied to the draw-down, thus

$$[\partial^2(\Delta z)/\partial r^2] + (1/r)[\partial(\Delta z)/\partial r] = (1/k)[\partial(\Delta z)/\partial t] \quad \ldots\ldots \quad (56)$$

and equation (2) is transformed into

$$v_r = -c[\partial(\Delta z)/\partial r] \quad \ldots\ldots \quad (57)$$

For a continuous draw-down with a constant pumping rate Q the solution of the differential equation (56) is given by

$$\Delta z = (Q/4\pi cd)\int_0^t e^{-r^2/4k(t-\tau)}/(t-\tau)d\tau \quad \ldots\ldots \quad (58)$$

in which d = thickness of the aquifer.

Letting

$$u = r^2/4k(t-\tau) \quad \ldots\ldots \quad (59)$$

we receive from equation (58)

$$\Delta z = (Q/4\pi cd)\int_\rho^\infty (e^{-u}/u)du = (Q/4\pi cd)E_1(\rho) \quad \ldots\ldots \quad (60)$$

in which

$$\rho = r^2/4kt \quad \ldots \quad (61)$$

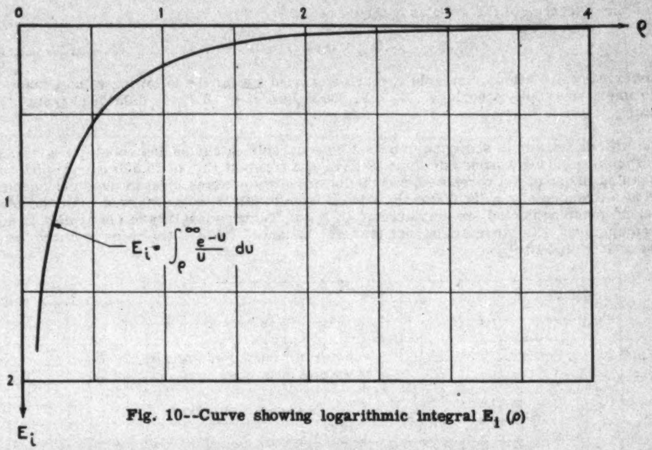


Fig. 10--Curve showing logarithmic integral $E_1(\rho)$

The E_1-function (logarithmic integral) [NIELSEN, 1906] has a definite value for any value of ρ. These values may be taken from available tables. Table 2 is extracted from a table used by C. V. THEIS [1935] and taken from the Smithsonian Institution Publication 3171 (1933). Table 2 is graphically represented by Figure 10, which also, in a general way, gives a view of the cone of depression. For small values of ρ the E_1-function may be calculated from the following expression:

$$E_1(\rho) = -\,0.577216 - \log_e \rho + \rho \quad \ldots \quad (62)$$

Table 2--Values of E_1 function

ρ	E_1	ρ	E_1	ρ	E_1	ρ	E_1
0.0	∞	1.0	0.21938	2.0	0.04890	3.0	0.01305
0.1	1.82292	1.1	0.18599	2.1	0.04261	3.1	0.01149
0.2	1.22265	1.2	0.15841	2.2	0.03719	3.2	0.01013
0.3	0.90568	1.3	0.13545	2.3	0.03250	3.3	0.00894
0.4	0.70238	1.4	0.11622	2.4	0.02844	3.4	0.00789
0.5	0.55977	1.5	0.10002	2.5	0.02491	3.5	0.00697
0.6	0.45438	1.6	0.08631	2.6	0.02185	3.6	0.00616
0.7	0.37377	1.7	0.07465	2.7	0.01918	3.7	0.00545
0.8	0.31060	1.8	0.06471	2.8	0.01686	3.8	0.00484
0.9	0.26018	1.9	0.05620	2.9	0.01482	3.9	0.00427

Observing the characteristics $E_1(0) = \infty$ and $E_1(\infty) = 0$, it is seen that the expression (60) satisfies the following initial and boundary conditions.

$$\Delta z = 0 \text{ for } t = 0 \quad \ldots \quad (63a)$$

$$\Delta z = \infty \text{ for } r = 0 \quad \ldots \quad (63b)$$

$$\Delta z = 0 \text{ for } r = \infty \quad \ldots \quad (63c)$$

The discharge across a circle with the radius r is obtained by means of equation (57), and becomes

$$Q_{rt} = Qe^{-r^2/4kt} \qquad (64)$$

and thus the discharge of the well, as it should be

$$Q_{rt} = Q \text{ for } r = 0. \qquad (65)$$

Numerical calculations, Example 5, may be carried out for the following values, taken from the aforementioned Höllvik borings: $E_w = 21{,}000$ kg/cm^2; $\epsilon = 0.3$; $\gamma = 0.001085$ kg/cm^3; and d = 5000 cm.

The Höllvik aquifer is supposed to have a considerable extension and constitute a true artesian basin. Pumping during a period of some 25 days at a constant rate of 15,500 cm^3/s(= 56 m^3/h) was executed in one of the boreholes, and the lowering of the water level in the other borehole, located at a distance of r = 220,000 cm(= 2.2 km) from the first, was observed. For the comparatively short pumping period, we may assume $E_S = \infty$. The permeability of the aquifer is not known, but by comparison with other sandstones (see, for instance, Table 1) the value of c may be taken at between 10^{-2} and 10^{-3}.

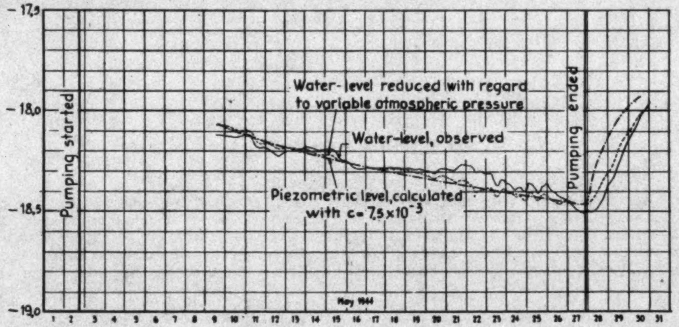


Fig. 11--Comparison between observed and calculated lowering of piezometric level during pumping tests in the Höllvik aquifer (Sweden)

Introducing c = 7.5 × 10^{-3} and the values of the second borehole given above (k = 4.85 × 10^5), in equation (60), we obtain the calculated successive lowering of the water level in this borehole as shown in Figure 11. For comparison, we have also plotted the actual water levels in the borehole during the pumping period, as observed and reduced with regard to the variable atmospheric pressure.

The pumping through a single well is often used for determining the permeability of an aquifer by applying the so-called Thiem's method, well known from ordinary handbooks. As pointed out by THEIS [1935], this method is open to serious criticism when used in large aquifers, because it presumes steady flow. In any case the application of formula (60) will give far more accurate

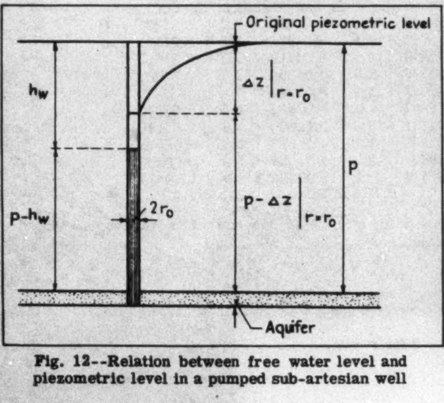


Fig. 12--Relation between free water level and piezometric level in a pumped sub-artesian well results, since the time effects are also taken into account thereby. Fortunately, it is not necessary to know the volume elasticity of the aquifer in such cases; as stated previously, the Meinzer effect sets in only after a longer pumping period, when the cone of depression has extended over a larger area.

In this connection attention may be called to some interesting pumping tests executed by Theis [1938, 1935]. In an analysis of the Meinzer effect, he makes use of a corollary to equation (60) and thereby finds a remarkable agreement between theory and tests for a large artesian aquifer. It seems, however, that even Theis adheres to the old postulate of considering the water as an incompressible fluid. In view of the comparatively short duration of the tests referred to, there is in the writer's opinion no doubt that the time effect appearing in these tests is not the Meinzer effect but that due to the compressibility of the water. It would seem logical, therefore, to consider the tests described by Theis for artesian aquifers as an excellent verification of the theory advanced in the present paper.

In the planning of pumping equipment for a pumped well and in the analysis of pumping tests it is of course necessary to take into account the loss of head due to friction, etc. in the well. The draw-down of the true water level in the well may be considerably in excess of the lowering of the piezometric level. According to Figure 12 we have at any time during the pumping period

$$\Delta z = (h_w - f) \text{ for } r = r_0 \quad \ldots \ldots \quad (66)$$

in which r_0 = radius of the well; h_w = draw-down of the true water level in the well; and f = loss of head in the well.

The loss of head in the well may be calculated by means of one of the current pipe formulas. To obtain a reliable value of the coefficient of roughness for the borehole, the writer would suggest the following method, involving pumping tests with different discharges.

The draw-down of the piezometric level and the loss of head in the well may be expressed in the form

$$\Delta z = \mu Q \text{ for } r = r_0 \quad \ldots \ldots \quad (67)$$

$$f = \lambda Q^{\kappa}(p - h_w) \quad \ldots \ldots \quad (68)$$

in which μ and λ are coefficients to be determined by the pumping tests, whereas κ may be taken, for instance, from Hazen-William's pipe formula ($\kappa = 1.85$). In many cases one may, for the sake of simplicity, put $\kappa = 2$.

Introducing the expressions (67) and (68) in equation (66), we obtain

$$h_w = \mu Q + \lambda Q^{\kappa}(p - h_w) \quad \ldots \ldots \quad (69)$$

Executing two pumping tests with different discharges Q_1 and Q_2, and observing the corresponding draw-downs of the true water level in the well, we obtain two equations of the form (69), from which the unknown coefficients μ and λ may be solved. In the application of the method it is necessary to extend both pumping tests over the same length of time and to start both tests with the same initial position of the piezometric level. In order to fulfill the latter requirement, at least approximately, the recovery period between the pumping tests must have a certain minimum length. The residual draw-down of the piezometric level during the recovery period may be investigated by the equation

$$\Delta z_r = (Q/4\pi cd)[E_1(\rho_1) - E_1(\rho_2)] \quad \ldots \ldots \quad (70)$$

in which Δz_r denotes the residual draw-down, and subscript 1 refers to the time since pumping started and subscript 2 to the time since pumping stopped. Formula (70) has been used for calculating the residual draw-down during the recovery period of the Höllvik pumping test shown in Figure 11.

The formula (60) is applicable to the entire aquifer except the very small portion inside the well itself, and excepting very large values of t. The former exception has no practical consequence, whereas the latter needs some further investigation. Through substitution in equation (60) we receive

$$\Delta z = \infty \text{ for } t = \infty \qquad (71)$$

which, of course, has no physical meaning with regard to aquifers in nature. As a matter of fact, the formula (60) is not valid when the lowered piezometric level in the well has reached the aquifer.

If for $t > t_a$ the piezometric level in the well is kept at the aquifer or else kept at a constant depth h_a below its original position, the pumped quantity of water cannot be maintained at the constant value of Q but will diminish and be a certain function of time. As far as the writer is aware, it is very difficult, if at all possible, to determine this function in explicit form. However, an approximate solution may be obtained by superimposing upon the discharge Q a number of charge and recharge sources of uniformly varying strength, applied at certain intervals and of such magnitude that at the end of each interval, the following condition is fulfilled:

$$\Delta z = h_a \text{ for } r = r_0 \qquad (72)$$

For a uniformly increasing rate of discharge

$$Q_t = qt \qquad (73)$$

the solution of the differential equation (56) is given by

$$\Delta z = (q/4\pi cd)\int_0^t \tau e^{-r^2/4k(t-\tau)}/(t-\tau)d\tau \qquad (74)$$

With the denominations (59) and (61) we receive after some transformations

$$\Delta z = (qt/4\pi cd)F(\rho) \qquad (75)$$

in which

$$F(\rho) = (1+\rho)E_1(\rho) - e^{-\rho} \qquad (76)$$

Consider again a sub-artesian well in which pumping at a constant rate Q has been going on until the piezometric level in the well at the time $t = t_a$ has reached the depth h_a. If, thereafter, the piezometric level in the well is constantly kept at this depth, we then obtain for $t > t_a$

$$\Delta z = (1/4\pi cd)\left\{QE_1(\rho_0) - \sum_{n=1}^{\infty} q_n[t_nF(\rho_n) - t_{n+1}F(\rho_{n+1})]\right\} \qquad (77)$$

where subscripts refer to the interval at the beginning of which the charge or recharge started, and where the values of q are to be determined in such a way that at the end of each interval the equation (72) is satisfied. The distribution of the yield will be represented by a polygonal line, the breaking points of which will correspond to the sought discharge. The obtained result will fall the closer to the true conditions, the shorter the intervals are taken.

Numerical calculations, Example 6, may be carried out with the values used in Example 5, and further $r_0 = 6.5$ cm and $h_a = 587$ cm. With these values we obtain the calculated lowering of the piezometric level in the well and the distribution of the discharge as shown in Figure 13.

In his work "The dead heart of Australia," J. W. GREGORY [1906] expressed the opinion that the artesian water of the Great Australian Basin must be of plutonic origin, and for this reason he was very pessimistic regarding the duration of the supply from the flowing wells. Gregory's conception of the nature of the artesian water appears to be wrong. Nowadays it is generally conceded that at least the major part of the water in this Basin, as in most other groundwater streams, is of meteoric origin, that is, rainfall entering the porous rocks through some intake beds at high levels. But all the same, the compression theory shows that, also from this standpoint, there is evidently a great danger of a dwindling yield. Even the most enthusiastic irrigator would likely be discouraged when looking at a discharge diagram such as that demonstrated in principle in Figure 8. The threatening water shortage is confirmed by the fact that a successive lowering of the piezometric level and a continuous decrease of the yield of the wells actually take place in the Great Basin, indicating that the water taken out by the wells for some time has exceeded the total natural capacity of the groundwater stream in the region in question.

Paying regard to the generations of people to come, it would assuredly be worth while expending research work, geological and technical, with a view to determining more accurately the flow-time effects in the Great Australian Basin and thus creating a more rational basis for the precautionary measures required to overcome the threat of water famine. The necessity of two

precautionary measures is obvious, namely, to control the discharge of all wells and to prevent, rigorously, any waste of water.

A. F. Samsioe of VBB, to whom the writer is indebted for valuable suggestions in the preparation of this paper, has called attention to the fact that the compression theory may also have a wider geophysical aspect. Referring, for instance, to the Libyan groundwater stream, it is known that the fossil springs found at the Kharga Oasis, some 500 km south of Cairo, were active and used by man for cultivating purposes in prehistoric time. According to HELLSTROM [1940], who has collected some interesting data concerning these springs, they were extinguished about 5000 years BC. As to the cause of the extinction no conclusive theory has been put forward. CATON-THOMPSON and E. W. GARDNER assume [1940] that it must have resulted from a change in the precipitation on the intake beds. J. BALL [1927] gives the clue to an alternative explanation when pointing out that the Nile at Dakka has eroded its channel down to the water-conveying sandstone. HELLSTROM [1940] takes this clue and assumes that the lowering of the piezometric level at Kharga may at least partly be due to the artesian water beginning to discharge into the Nile at some prehistoric time. According to the compression theory, there can be no doubt that this cut of the Nile into the aquifer, thousands of years ago, has played an important rôle for the flow in the Nubian sandstone. It seems probable that when the cut was established a gradual lowering of the piezometric level took place, the activity of the flowing springs at Kharga began to diminish, and the culture developed by prehistoric man in the oasis died.

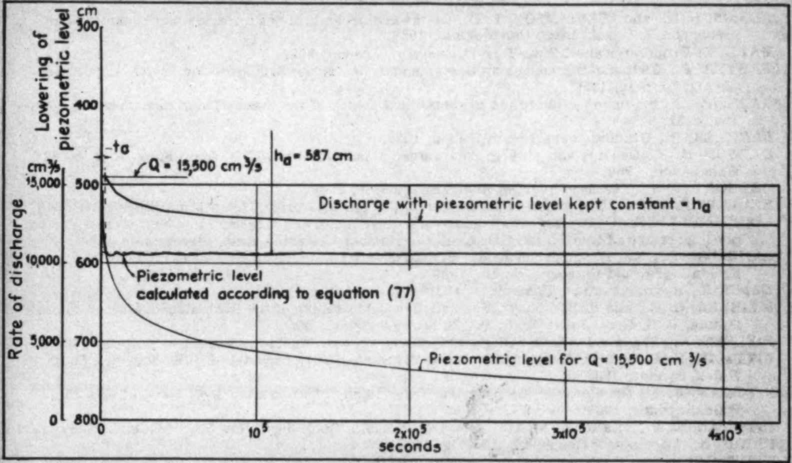


Fig. 13--Calculated effect in well first pumped with constant rate of discharge and then with piezometric level kept constant for $k = 4.85 \times 10^5$ cm^2/sec, $r_0 = 6.5$ cm, and $h_a = 587$ cm

Conclusions

The foregoing general investigation shows that the time effect due to compression has a far-reaching influence upon the flow in large artesian aquifers, such as those mentioned in the abstract. Unfortunately, the lack of fundamental data--in regard to the permeability of the aquifers, the spacing of existing wells, the successive boring of new wells, etc.--makes it impossible here to demonstrate the calculated time effect in actual figures. Nevertheless, in the present state of the investigation certain definite conclusions may be drawn which have a great bearing upon the correct interpretation of this important geophysical problem. These conclusions may briefly be summarized as follows:

(1) The natural flow in a large artesian aquifer will remain in a state of relative hydrodynamic equilibrium, provided the yearly inflow at the intake beds is constant.

(2) The aquifer contains a vast storage of water due to compression, over and above the natural capacity of the subterranean stream.

(3) When artesian wells are discharging water freely or sub-artesian wells are being pumped heavily, some of the water is drawn from storage due to compression, especially during the first period of the well's "lifetime."

(4) It is very dangerous to estimate the safe yield of a well district without taking into account the storage due to compression, because the discharge of a large group of wells may be many times greater than the original or ultimate natural capacity of the groundwater stream.

(5) Restoring the once lowered piezometric level by raising the water level on the intake beds would require a very long time for places at considerable distance from the intake beds.

These conclusions are valid, even if the volume elasticity of the aquifer should be negligible, and, consequently, the time effect be caused solely by the compressibility of the water. It should be noted that the last-mentioned time effect will always be prevalent.

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ON THE LOGARITHMIC-PROBABILITY LAW

A. A. Kalinske

The normal error law, known also as the Gaussian or Laplacean law, describes the frequency distribution of many physical measures in physics and engineering. It is expressed as

$$\phi(x) = (1/\sqrt{2\pi}\sigma_x)e^{-(x - \bar{x})^2/2\sigma_x^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $\phi(x)$ is the frequency function, x is the variate, $\bar{x}$ the arithmetic mean, and σ_x the so-called standard deviation, which is equal to $\sqrt{\overline{(x - \bar{x})^2}}$, the bars indicate arithmetic averages. This function is symmetrical with respect to $\bar{x}$, and the probability of occurrence of x between x and $x + dx$ is equal to $\phi(x)dx$. The standard deviation, σ_x, characterizes this probability function completely. Values of $\phi(x)$, its derivatives, and the areas under this curve, such as $\int_0^x \phi(x)dx$, which indicates the probability of occurrence of the variable between 0 and x, are tabulated in numerous places. Thus it is very convenient to use this frequency function in any analysis of statistical data.

Unfortunately, many statistical data encountered in the field of hydrology do not behave in accordance with the normal law. Many times the frequency-distribution curve is asymmetrical or "skewed." Mathematical statisticians have developed various functions to fit such data; however, such functions are usually quite complex, since they contain several parameters which must be evaluated from the data, while the normal error law has only $\bar{x}$ and σ_x. Thus the comparison of one set of data with another becomes quite involved. In order to make use of the relative simplicity of the normal law, it has been found that if x does not follow this law, some function of x might follow it quite well. For example, it has often been noted that many times river-discharge data and sand sizes will follow the normal law if the logarithm of the flow of river or the diameter of sand is used instead of the actual values themselves [see "References" at end of paper, FOSTER, 1924; HATCH and CHOATE, 1929; HAZEN, 1930]. This means that if x is our varying quantity, then the frequency of occurrence of $\log x$ is in accordance with the normal law. The frequency function is then

$$\phi(\log_e x) = (1/\sqrt{2\pi}n)e^{-(\log_e x - m)^2/2n^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $\log_e x$ = logarithm of x to base e. It can be shown quite readily that m is the arithmetic mean of the values of $\log_e x$ and n is the standard deviation of the $\log_e x$ measures. The arithmetic mean of the logarithms of a set of measures is in reality equal to the logarithm of the geometric mean. The parameters m and n must, of course, be evaluated by arithmetic computation, or graphically, as will be discussed later. The values of m and n characterize the log-probability law completely, and it can be demonstrated that the arithmetic mean, $\bar{x}$, and the standard deviation, σ_x, of the x's themselves are functions of m and n. Since $\int_{-\infty}^{\infty}(\log_e x)dx = 1$, and since the frequency of x is identical to that of $\log_e x$ we have the following expressions for $\bar{x}$ and σ_x.

$$\bar{x} = \int_{-\infty}^{\infty} x\phi(\log_e x)d(\log_e x) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\sigma_x^2 = \int_{-\infty}^{\infty} (x - \bar{x})^2\phi(\log_e x)d(\log_e x) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

These expressions can be integrated by making the substitution $\log_e x = y$, and there is then obtained

$$\bar{x} = e^{m + n^2/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\sigma_x = \bar{x}(e^{n^2} - 1)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Though mathematicians look with disfavor on the use of graphical methods in the evaluation of statistical parameters, engineers find them very convenient and time saving, especially if the accuracy required is not too great. There has been developed so-called probability paper, both of the arithmetic and logarithmic type, and if a set of measures plots as a straight line on these papers, it is known that the data follow either the ordinary normal law or the logarithmic normal law. Once the straight line is drawn, all the necessary parameters such as $\bar{x}$ and σ_x or m and n can be very easily obtained.

Using the arithmetic-probability paper, the value of $\bar{x}$ is that value where the straight line crosses the 50-per cent ordinate. From the probability integral it can be easily shown that the value of σ_x is equal to the difference between the value of x intersected by the 84.13-per cent ordinate on the probability scale and the 50-per cent value of x, which is $\bar{x}$. It is thus apparent that the standard deviation is proportional to the slope of the straight line.

Since the logarithmic-probability paper commercially available is constructed using logarithms to the base ten, the value of $m = 2.3 \log_{10} M_g$, where M_g is the value of x on the log scale intersected by the 50-per cent ordinate. (Note that M_g is really the geometric mean of the x's.) The value of $n = 2.3 \log_{10} \sigma_g$ where σ_g is the value obtained by taking the ratio of the values of x intersected by the 84.13-per cent and the 50-per cent ordinates. (Log σ_g is, of course, the standard deviation of the logarithms of x). Once m and n have been evaluated, the values of $\bar{x}$ and σ_x can be obtained from equations (5) and (6).

Logarithmic-probability paper has already been used with considerable success in sediment-size analysis and the study of river-flow data; it is hoped that this brief exposition of the mathematics relating to its use will be of value to those who have occasion to employ this paper in engineering statistics.

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DISCUSSION

W. B. Langbein (U. S. Geological Survey, April 4, 1946)--We are indebted to Kalinske for his competent demonstration of two useful devices to encourage the use of logarithmic-probability paper. As Kalinske shows, the graphical determination of otherwise complex statistical parameters is indeed helpful.

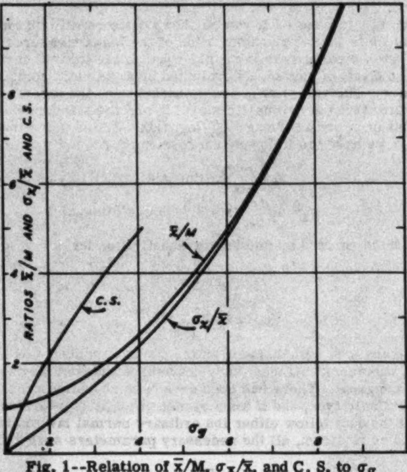

Fig. 1--Relation of $\bar{x}/M$, $\sigma_x/\bar{x}$, and C. S. to σ_g

Although the arithmetic mean is simple to compute, the computation of the standard deviation is another matter. I find even the so-called "short-cut" methods tedious. Kalinske's proposals can be simplified by combining formulas (5) and (6) with $n = 2.31 \log_e \sigma$-g and expressing the gross relationships of σ_g to $\bar{x}/M$ and $\sigma_x/\bar{x}$ graphically. I have shown these graphs in Figure 1. The ratio $\bar{x}/M$ is merely the ratio between the arithmetic and geometric means, and the ratio σ_x/M is recognized as the coefficient of variation. I have also included a curve showing the coefficient of skew (C. S.) in terms of σ_g. The graph on Figure 1 applies to the ratio between the values corresponding to the 84.13-per cent and 50-per cent ordinates. A similar graph could be prepared for any pair of ordinates, but these two seem to be most significant in a statistical sense.

In applying methods such as these, there is the problem of deciding whether a straight line is appropriate. The points may plot in such a way that some curvature is indicated. Should the curvature be discounted as due to errors of sampling or should it be given full weight and consideration? Where the matter is important, statistical tests may be applied to aid in formulating judgment. However, unless straight lines can be drawn, the method proposed by Kalinske appears inapplicable. Where the difference between plotted points and the rectified graph is large, the statistical parameters may differ considerably from those obtained directly from the data. However, some may argue that in such cases the rectified graph and its associated parameters may be more representative of the population than the raw data.

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STRUCTURAL CONTROL OF ORE DEPOSITION AT KASAAN PENINSULA, SOUTHEASTERN ALASKA

L. A. Warner and E. N. Goddard

Abstract

(Published by permission of the Director, United States Geological Survey)

Copper-bearing magnetite deposits and associated copper deposits at Kasaan Peninsula, Prince of Wales Island, southeastern Alaska, have been known for many years and have been mined to some extent for their copper content. At the beginning of World War II, the development of war industries in the Pacific northwest focused attention on the deposits as possible sources of iron ore. From 1942 through 1944 the United States Geological Survey made detailed studies of most of the ore deposits and at a few of the more promising localities diamond-drilling operations were carried on by the United States Bureau of Mines. The deposits are for the most part small and irregular but of relatively high grade. The chief ore minerals are magnetite, pyrite, and chalcopyrite, and the gangue consists largely of skarn minerals, including garnet, epidote, diopside, and hornblende. The deposits are presumably of pyrometasomatic origin, but whereas deposits of this type are commonly replacement bodies in limestone, at Kasaan Peninsula limestone seemingly was a poor host rock for the ore.

Most of the country rock on the peninsula is greenstone of andesitic composition and probable Mesozoic age. Included in the greenstone are rocks of sedimentary origin believed to be of Paleozoic age. These consist of limestone and various clastic rocks, including siltstone, graywacke, quartzite, and conglomerate, some of which are calcareous. All of the sedimentary rocks have been somewhat metamorphosed, the limestone having been completely marmorized. Structural relationships suggest that the andesitic material is mainly in the form of huge sills which intruded the sedimentary sequence. Intrusion is believed to have progressed to the extent that the intrusive material was far more abundant than the host rock, and the sedimentary rocks are thought to have been broken into discontinuous slabs which now appear as crenulated lenses and layers in the greenstone. The greenstone and included sedimentary rocks were later folded and fractured and were intruded by numerous dikes and stock-like bodies of igneous material ranging in composition from gabbroid to keratophyric types. At the close of the intrusive cycle the region was faulted and ore bearing solutions, percolating upward along faults and dikes, replaced brecciated greenstone and lenses of calcareous clastic material but replaced limestone in only a few places.

The ore deposits are commonly associated with areas in which rocks of sedimentary origin comprise a substantial part of the country rock. Only small pods and stringers of ore have been found in areas where such rocks are not exposed or cannot be reasonably assumed to be present.

During the orogeny which preceded and accompanied the intrusion of the numerous dikes and stocks, the greenstone doubtless yielded with difficulty to the forces of deformation. However, in places where the greenstone contained abundant layers of sedimentary material, zones of weakness existed and rock failure was more common. These zones of weakness became zones of principal deformation in which the rocks were folded, faulted, and brecciated. Such zones of principal deformation were best prepared to receive the mineralizing solutions. The extent to which the rocks were replaced presumably depended upon their composition and their accessibility to the solutions. The limestone, having deformed by plastic flow and recrystallization, was much less permeable than the foliated clastic sediments and the fractured greenstone and contains almost no ore. Low grade ore with skarn is found in broken greenstone within and adjacent to the major ore bodies. In places where the greenstone was sufficiently pulverized replacement was practically complete. The more calcareaous of the foliated and broken lenses of clastic sediments were probably the rocks most commonly attacked by the mineralizing solutions. Much of the ore and skarn rock shows a banding similar to that found in certain of the clastic rocks and nearly all stages of replacement between the partly altered clastic rocks and the banded ore and skarn have been encountered.

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ACTIVITIES IN TECTONICS OF RESEARCH COMMITTEE OF AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

Philip B. King

During 1945 and 1946, the Research Committee of the American Association of Petroleum Geologists, under the chairmanship of Shepard W. Lowman, has been engaged in "a reconnaissance survey of research in petroleum geology and allied sciences with explicit reference to exploration" in order "to formulate a comprehensive research program which the American Association of Petroleum Geologists may adopt as its recommendation for that research most needed to improve our ability to find oil" [see "References" at end of report, LOWMAN, 1945]. In order to make this survey, the field was divided among a number of subcommittees, including a Subcommittee on Tectonics, of which the writer was chairman. Preliminary reports, discussing the research possibilities in the various fields covered by the subcommittees, were submitted in January, 1946, and concrete recommendations were formulated by the Research Committee at the Chicago meeting of the Association in April 1946 [LOWMAN, 1946]. Final reports of the subcommittees will be published later in 1946 in the Bulletin of the American Association of Petroleum Geologists.

In preparing the report of the Subcommittee on Tectonics, information and suggestions were obtained by correspondence with other members of the Subcommittee, A. H. Bell, R. A. Liddle, and W. T. Thom, Jr., with consultants W. H. Bucher, Ernst Cloos, James Gilluly, M. K. Hubbert, C. R. Longwell, and C. W. Tomlinson, and geologists generally throughout the country. Large amounts of data were obtained which are quoted in the final report of the subcommittee. Not all of the suggested projects given in this report could be acted on at this time. Some are outside the direct field of petroleum geology although of considerable indirect importance. Many await further formulation as to specific objectives, personnel, funds needed, equipment needed, etc. On others, it was considered probable that oil companies would do this or similar work as a part of their regular commercial operations.

Of the projects described in the final report of the Subcommittee, the following have been specifically favored for immediate or later action:

Recommended projects--Projects deserving the support of the AAPG in order that they may be initiated or completed: (a) Completion of the areal geologic map of the United States on a scale of approximately an inch to a mile, in some standardized, easily accessible form, either by Federal or State agencies; (b) completion and revision of state geologic maps on a standard scale of 1:500,000, by Federal and State agencies; and (c) revision of Tectonic Map of United States through cooperation of National Research Council, United States Geological Survey, the AAPG, and geologists generally.

Commended projects--Projects under way that are favored by the subcommittee: (a) Oil and gas investigations by Fuels Section of United States Geological Survey (mainly regional stratigraphic and structural studies, initiated as a phase of war work); (b) work of Yellowstone-Bighorn Research Association (regional tectonic studies in northwest Wyoming and southwest Montana); (c) geologic structure maps of states (maps showing structure contours, faults, axes, etc., on 1:500,000 or 1:1,000,000 scale; two have been published and others are in preparation.); and (d) contour map of United States on top of basement rocks (sponsored by Special Committee on Geophysical and Geological Study of Continents of American Geophysical Union).

Projects needing formulation--Projects favored by Subcommittee, but for which details have not yet been worked out: (a) Detailed study of salt domes (especially of flow structure and other features exposed in mine workings); (b) comprehensive studies of regions (compilation of maps of tectonic provinces, based on outcrops and drill records, showing structure contours, isopachs, paleogeology, and paleogeography. Many good studies have been made, but more are needed.); (c) studies of fracture systems (jointing, faulting, etc., in relation to local structural features, and in regional pattern); and (d) laboratory experiments (experiments with scale models, to aid in the explanation of the origin of structural features according to the principles of the mechanics of deformable bodies).

In addition to these, the following two projects with tectonic implications were recommended by the Research Committee upon the advice of other subcommittees: (a) Completion of topographic map of the United States and presentation on both large and small scales (for example, 1:62,500 and 1: 500,000); and (b) increase of number of gravimetric base stations to one station for each 2500 sq mi; interconnect pendulum stations with gravity-meter traverses; run gravity meter profiles across gravity anomalies and major tectonic features (recommended to United States Coast and Geodetic Survey).

The relation of the American Association of Petroleum Geologists to research projects has been summarized as follows: "Much research has been done by individuals or groups within the Association. Such activity appears to be in conformity with our interest and with the Association's constitution, but it does not appear to be our interest to assume the responsibilities of a research foundation. It is recommended that the Association should not attempt to do major research projects, but that we should catalyse them, by formulating such major projects and attempting to place them among existing research agencies" [LOWMAN, 1945, p. 789].

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RECENT PROGRESS IN GEODETIC SURVEYS IN THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the year ending June 30, 1946, most of the activities of the field survey parties of the Division of Geodesy of the United States Coast and Geodetic Survey have been in the Columbia River Basin in connection with the development of that area for navigation, water power, and flood control. The Basin comprises a large area extending into Idaho, Wyoming, Montana, Washington, and Oregon (see Fig. 1). Within this area are some of the roughest sections of terrain to be found on the North American Continent. The deep canyons of the Snake and Salmon Rivers rival those of the Grand Canyon in Arizona. Transportation of personnel and equipment in Idaho is very difficult, particularly along the rivers. The triangulation parties operating in this region used Army reconnaissance cars and weapon carriers, pack trains, and airplanes in bringing supplies into isolated regions. The leveling party operating along the Salmon River used barges from Salmon, Idaho, downstream, establishing camp each night as the progress of the party warranged. Numerous rapids had to be traversed. Similarly the leveling party operating along the Snake River had to make use of local boat facilities in the section between Weiser and Lewiston, Idaho.

Four triangulation parties are working in this area operating along the Snake River from Weiser to Lewiston, Idaho, and thence to Pasco, Washington; along the Salmon River from Salmon, Idaho, to its confluence with the Snake River near Grangeville, Idaho; along the Deschutes River in Oregon from Redmond, Oregon, to the mouth; along the John Day River from the Middle Fork to the mouth at Arlington, Oregon; along the Grande Ronde River and along Henry's Fork, Idaho. One leveling party, consisting of three observing units, operated in this area throughout 1945. It is expected that field work will continue in this region throughout the summer season of 1946, with three triangulation parties and one level party of four units operating continuously.

For the triangulation work in the Columbia River Basin, many supplemental points were occupied in addition to the main scheme stations. Numerous picture points were located also for the use of the photogrammetrists. Vertical angle measurements were made for the determination of elevations of stations by trigonometric means.

Triangulation and leveling were accomplished in the Missouri River Valley in connection with the development of that region for water power, navigation, and flood control. An arc of triangulation was provided in North Dakota from Williston to Minot, North Dakota. This arc will be continued during the present season to make a connection to established control at Devils Lake, North Dakota. Connections between Missouri River Commission marks and established stations of the United States Coast and Geodetic Survey were made at numerous places along the Missouri River so that the control of the Commission could be adjusted and placed on the North American 1927 Datum.

The leveling party operating in the Missouri River Valley consisted of three units and did considerable work in Missouri and the Dakotas. The areas in which work is being conducted are given priorities by the Corps of Engineers. It is expected that these parties will operate in this area throughout the coming field season, will move south during the winter, and will again resume operations in the Missouri River Valley in the spring of 1947.

Triangulation was carried on in the southern part of Indiana in the vicinity of Boonville. This is primarily for the United States Geological Survey and is intended to make control available for the mapping program of that organization. It is expected that two triangulation parties will operate in Indiana during the 1946 summer season and also the following spring and summer. One level party consisting of four units is operating in Indiana at the present time and is based at Greencastle, Indiana, establishing vertical control for the use of the topographers of the United States Geological Survey.

A triangulation unit has operated extensively in the Southwest and has executed a scheme of triangulation northward from Silver City, New Mexico, to the Colorado-New Mexico boundary,

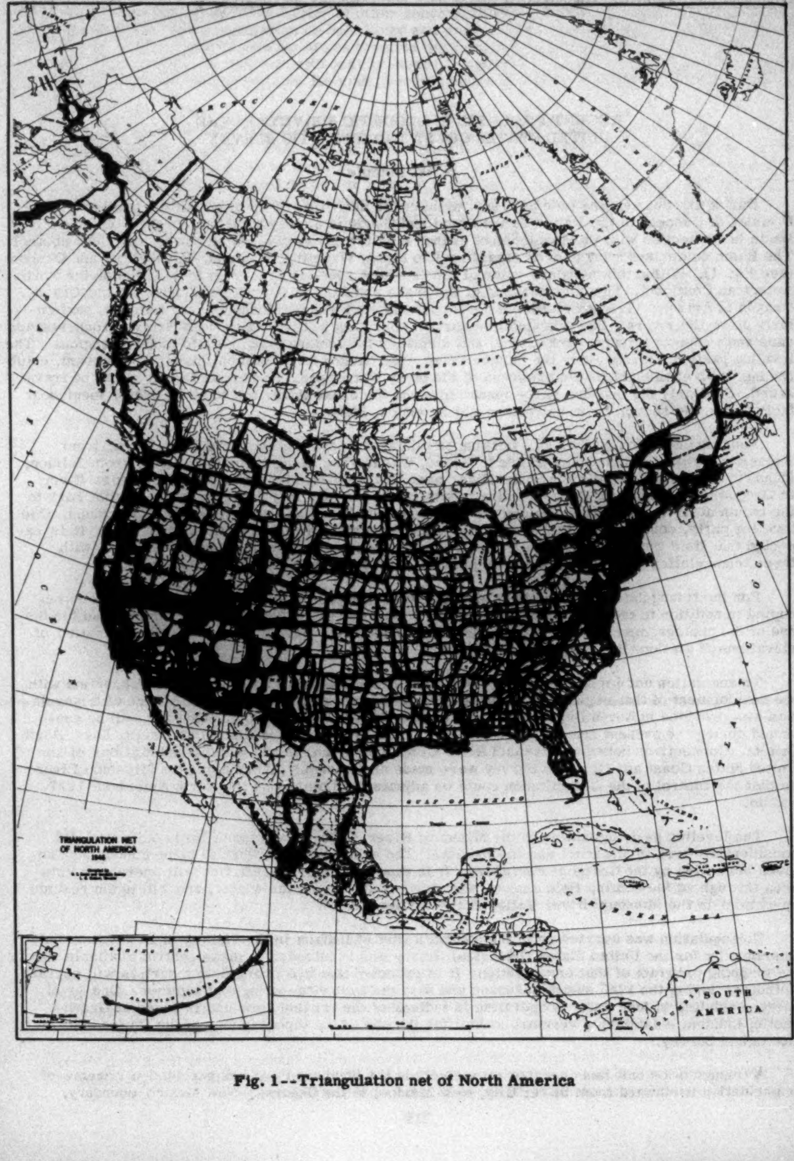
ARCTIC OCEAN
TRIANGULATION NET
OF NORTH AMERICA
1946
GULF OF MEXICO
CARIBBEAN SEA
SOUTH AMERICA
BERING SEA
ALEUTIAN ISLANDS

Fig. 1--Triangulation net of North America

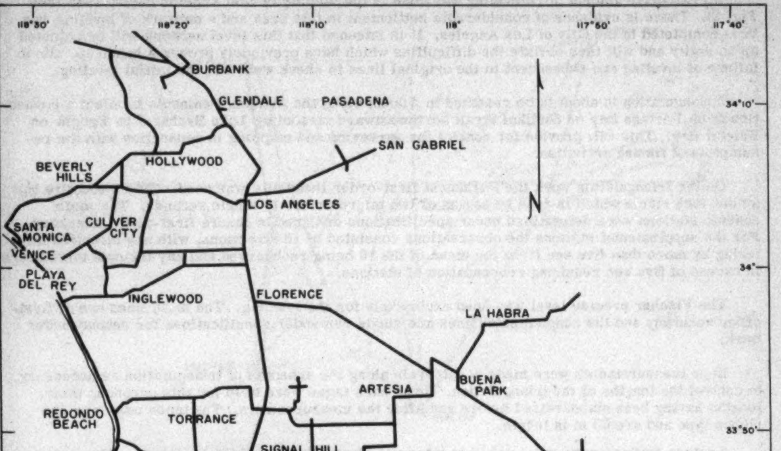
118°30'
118°20'
118°10'
118°
117°50'
117°40'
34°10'
34°
33°50'
33°40'
BURBANK
GLENDALE
PASADENA
SAN GABRIEL
BEVERLY HILLS
HOLLYWOOD
LOS ANGELES
SANTA MONICA
CULVER CITY
VENICE
PLAYA DEL REY
INGLEWOOD
FLORENCE
LA HABRA
BUENA PARK
ARTESIA
REDONDO BEACH
TORRANCE
SIGNAL HILL
WILMINGTON
HARBOR CITY
SAN PEDRO
LONG BEACH
SEAL BEACH
SANTA ANA
PT. FERMIN
IRVINE
EL TORO
NEWPORT BEACH
LAGUNA BEACH
SAN JUAN CAPISTRANO
MILES
0
5
10

Fig. 2--Leveling net--Los Angeles, California

thence eastward along this boundary to Trinidad, Colorado, and southward from Antonito, Colorado, to Santa Fe, New Mexico. This party also worked in the Sulphur Springs Valley of Arizona and at present is operating in the Tonto National Forest in the vicinity of Phoenix, Arizona.

Triangulation and leveling operations were conducted last winter (1945-46) in Texas in the vicinity of Fort Worth and Dallas and along the Trinity River. These control surveys are needed by the Corps of Engineers in their plans for the development of the Trinity River. It is expected that work in this area will be resumed in the fall of 1946.

Triangulation and leveling were extended in Alabama and Mississippi along the Black Warrior and Tombigbee Rivers. These are winter assignments and the parties that are now operating in the north will resume operations in these regions next fall and winter.

An extensive amount of releveling was done in the vicinity of Los Angeles during 1945 (see Fig. 2). There is evidence of considerable settlement in this area and a network of leveling has been completed in the City of Los Angeles. It is intended that this level network will be adjusted as an entity and will thus obviate the difficulties which have previously proven a handicap, due to failure of leveling run subsequent to the original lines to check well with the initial leveling.

Triangulation is about to be resumed in Alaska along the Alaskan Peninsula to effect a connection from Portage Bay on Shelikof Strait northwestward straddling Lake Becharof to Egegik on Bristol Bay. This will provide for control for surveying and mapping in connection with the resumption of fishing activities.

On the triangulation work the Parkhurst first-order theodolite was used. This theodolite has a nine-inch circle which is read by means of two micrometers to single seconds. The main scheme stations were determined under specifications designed to insure first-order accuracy. For the supplemental stations the observations consisted of 16 directions, with any direction differing by more than five sec from the mean of the 16 being reobserved and any triangle misclosure in excess of five sec requiring reoccupation of stations.

The Fischer precise level was used exclusively for the leveling. The main lines are of first-order accuracy and the supplemental lines are single run under specifications for second-order work.

Base measurements were made at intervals along the schemes of triangulation as necessary to control the lengths of the triangulation. Invar base tapes were used for this purpose, their lengths having been standardized before and after the measurements. The tapes used are the ribbon type and are 50 m in length.

Laplace stations were established at intervals along the arcs of triangulation. The azimuth observations were made by the triangulation party during the course of their triangulation observations. The determinations of the latitude and longitude at the Laplace stations were made by an astronomic party at a later date using the Bamberg broken-telescope transit and under specifications requiring first-order accuracy.

Astronomic observations were made at Brownsville, Texas, for the purpose of obtaining an indication of the relative accuracy of observations made with the pendulum astrolabe and those made with the Bamberg broken-telescope instrument. A comparison was made also between the method of determining azimuths by observations on stars in the prime vertical and those by observations on Polaris. An account of the results of this work is the subject of a paper by other representatives of this Bureau [see "Experimental position determination by pendulum astrolabe," by F. R. Gossett and A. D. Sollins under Papers in Geodesy, this issue].

The United States Hydrographic Office, Navy Department; the Corps of Engineers, United States Army; and the United States Coast and Geodetic Survey cooperated in the extension of triangulation from the Florida mainland to the Bahamas by observations on flares released from airplanes (see Fig. 3). The distance between the islands and the mainland varies from 60 to 100 mi. Three stations on the mainland whose latitudes and longitudes were known were occupied, and three stations were established on the islands and their positions determined. At each of the stations on the mainland and on the islands an eccentric set-up was also used and occupied. Simultaneous observations were made at intervals at each of these stations on flares released at specified locations between the islands and the mainland. The flares of 100,000 candlepower attached to parachutes were usually released from an elevation of 17,000 ft and burned from four to five min. A total of 32 pointings were obtained at each specified location, as many as four pointings being made on each flare. The position of each flare was computed from the observations at the main scheme stations on the mainland and then the locations of the stations on the islands were obtained by the three point fix method by using the computed location of the flare.

As a test of the accuracy of the method the eccentric stations established on the mainland, considered as unknown stations, were located by the three point method. A comparison of this computed position with that as obtained by the eccentric distance and direction from the main station indicated that an accuracy of from one part in 72,000 to one part in 150,000 may be obtained. The method, which is quite costly compared with ordinary field methods where stations are intervisible, requires excellent weather conditions, well-trained observers, and airplane pilots who are good navigators.

Training grants have been continued to South American nationals in connection with the program of the State Department to promote friendly relationships with the Latin American Republics.

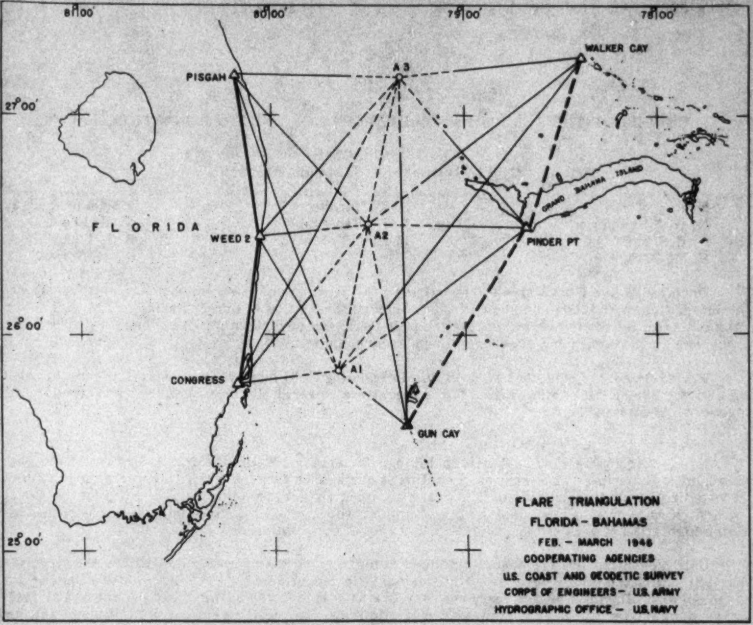
81 00'
80 00'
79 00'
78 00'
27 00'
26 00'
25 00'
PISGAH
A 3
WALKER CAY
FLORIDA
WEED 2
A2
PINDER PT
GRAND BAHAMA ISLAND
A1
CONGRESS
GUN CAY
FLARE TRIANGULATION
FLORIDA - BAHAMAS
FEB. - MARCH 1946
COOPERATING AGENCIES
U.S. COAST AND GEODETIC SURVEY
CORPS OF ENGINEERS - U.S. ARMY
HYDROGRAPHIC OFFICE - U.S. NAVY

Fig. 3--Triangulation--Florida to Bahama Islands

A total of six training grants in geodetic surveying are offered each year to citizens of the South American countries. The recipient must be a college graduate and be engaged in precise surveying activities in his own country. The training grant provides for the payment of the travel to and from the United States and also permits an allowance for living expenses while in the United States. Six months are spent in the field and two months in the Washington Office becoming acquainted with the various surveying activities of the Bureau. This program has proven very successful and it is planned to continue it under the present arrangements with the State Department.

Legislation providing for the use of plane coordinates in property description was passed by the Virginia Legislature during the year. This makes a total of 20 states which have adopted such legislation.

As in past years, the National Bureau of Standards has cooperated in standardizing base tapes and in graduating theodolite circles.

Shortages of materials, particularly of transportation equipment such as trucks, make it rather difficult to conduct field operations efficiently and economically. Personnel requirements are usually being met although there is some difficulty in obtaining competent personnel who can carry on the supervisory duties of the higher positions.

U. S. Coast and Geodetic Survey,
Washington, D. C.

(Manuscript received July 18, 1946; presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 28, 1946; open for formal discussion until March 1, 1947.)

Transactions, American Geophysical Union Volume 27, Number V October 1946

REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1945-46

H. G. Wilm, Chairman
C. W. Thornthwaite, Assistant Chairman

E. A. Colman
N. W. Cummings
A. R. Croft
H. T. Gisborne
S. T. Harding
A. H. Hendrickson
Marvin D. Hoover
Joseph Kittredge
C. H. Lee
H. J. Lutz
C.-G. Rossby

Once more this Committee is reporting on the progress of work which has been severely restricted, first by wartime and now by postwar conditions. One of our contributors, M. D. Hoover, was called to the armed forces during the past year, and several others have been kept from active research by the continuing pressure of nonresearch duties.

We all sincerely hope that work in this interesting field may be brought back to normal levels of activity during the coming year. In the meantime, several statements on real and worth-while progress are available.

E. A. Colman (California Forest and Range Experiment Station)--Since last year we on the San Dimas Experimental Forest have continued our search into the evapotranspiration problem in two directions, the analysis of five years of soil-moisture sampling data, and the further development of an electrical soil-moisture instrument, which would facilitate future studies of this kind. Some highlights of both efforts may be of interest to the Committee.

Until recently, we have been disinclined to make more than vague promises for the success of our soil-moisture meter because of the periodic disappointments we have encountered during its development. During the last year, however, we have made very satisfactory progress and feel that our promises can now be somewhat more definite. The instrument consists of a soil unit and a meter. The soil unit is essentially a layer of "fiberglas" fabric sandwiched between two monel screen electrodes, all mounted on a plastic base. We measure the electrical resistance of the fiberglas between the electrodes. This resistance varies with its moisture content, which, in turn, is dependent upon the moisture content of the soil surrounding the unit. As a result of the wide range of pore sizes present in the fiberglas and the relatively large size of the largest pores, it is possible to measure soil moistures over the soil-moisture range from air dryness to saturation. The measuring meter is a direct-reading alternating-current ohmmeter. Its power supply is entirely self-contained. This type of meter, while perhaps less sensitive than a well-designed Wheatstone bridge, is sufficiently accurate for the job and has the additional advantage of instant indication of resistance.

Laboratory and field studies of the moisture instrument in its present form have been carried on for the last year and seem to bear much promise of success. We would welcome the opportunity to have some of the soil units tested in other parts of the country so that we can learn how they respond to widely varying soil and climatic conditions.

From the soil-moisture data accumulated on the San Dimas Forest we have learned some things not mentioned in last year's report. We have, for instance, found it useful to separate the year into what might be called "soil-water storage periods." Their occurrence depends upon (1) the "permanent" or ephemeral condition of water storage in the soil, (2) the possibility of rainfall contributing directly to groundwater flow of streams, and (3) whether soil-water storage as a whole is increasing or decreasing. Starting with the beginning of the rainy season, a year is divided into the following soil-water storage periods; (1) the intermittent storage period, (2) the increasing storage period, (3) the maximum storage period, (4) the decreasing storage period, and (5) the minimum storage period. Period (1) may be missing if early storms are large. Period (3) may not occur during years of low rainfall. Such a division of the year has made it possible to distinguish (1) the early and late parts of the rainy season during which rain reaching the soil is lost very promptly by evapo-transpiration, (2) the period during which seepage into groundwater storage is possible (maximum storage), and (3) the soil-wetting and drying periods.

It has become evident from this study that a certain portion of each year's rainfall in Southern California contributes no water for human use. This is the rain that occurs in small storms early in the rainy season and during the summer, when the soil is quite dry. This rain wets the soil to a depth of only a few inches and is lost again to the atmosphere before the next storm. It therefore makes no contribution either to the recharge of the soil-water reservoir or to groundwater storage. It does play a part, of course, in the weathering of the soil and the decomposition of organic matter. It may also be important in reducing fire danger, since even such small water additions maintain or replenish leaf moisture content and thus decrease the inflammability of chaparral vegetation.

We were somewhat surprised to find that fully half the total annual evapotranspiration water losses of some of these mountain soils took place during the winter rainy season. Evapotranspiration rates were actually somewhat higher--averaging .07 inch per day--during the rainy season than at any other time of the year. We feel that this is a result of the high average moisture content of the soil during this part of the year and of the relatively high air temperatures that prevail between storms.

The analysis of the San Dimas soil-moisture study is being continued and will be combined with that of similar studies made in the foothills of the middle Sierra Nevada so that we can reach a more comprehensive understanding of the annual soil-water storage cycles in California mountains.

N. W. Cummings (San Bernardino, California)--So far as the broad fundamental problems of evaporation and transpiration are concerned, the type of discussion needed at the present time is one which might be said to belong in the general domain of philosophy of science.

Only rarely does the literature contain even a crude indication of the error of an evaporation calculation or estimate. This is a serious fault, because seldom if ever is any worthy objective gained by assigning a numerical magnitude to any physical quantity, unless the assigned value is accompanied by some sort of index of its precision. The index should, of course, have some kind of valid support.

Something should be done to bring this philosophic principle to the attention of workers in our field, for it underlies everything worth doing or saying which is in any way related to the activity of our Committee. I do not mean to suggest that the precision must always be high, but merely that, high or low, the magnitude of the error should be indicated.

H. T. Gisborne (Northern Rocky Mountain Forest and Range Experiment Station)- Recent developments in the northern Rocky Mountain region accentuate the need of examining the field of hydrologic research and apportioning or recommending assignment of supervision and major responsibility for specific portions to the best qualified agencies involved. With the United States Geological Survey as the official stream-gaging agency, the United States Weather Bureau as the official weather and flood forecaster, the Soil Conservation Service predicting irrigation water supplies, the Reclamation Service constructing irrigation facilities, the Engineer Corps handling the navigation and power phases, the Forest Service protecting and manipulating vegetative cover at the headwaters, and all six agencies and some others engaged in snow-water measurement and other meteorologic, hydrologic, biologic, and civil engineering research, the overlap and confusion are becoming more than recognizable.

Study of this deteriorating situation should be made by some impartial, unbiased organization. The American Geophysical Union would appear to be ideally constituted to contribute most efficiently to such an analysis, with consequent recommendations.

H. J. Lutz (Yale University School of Forestry)--During the past two summers I have carried on water-table measurements in a swamp forest and on the adjacent upland in southern New Hampshire. Notable diurnal fluctuations in the water table have been observed, and during the coming year it is planned to obtain continuous records using water-stage recorders.

C. W. Thornthwaite (U. S. Soil Conservation Service, Washington, D. C.)--In the Committee report for 1943-44 I presented a formula for determining potential evapotranspiration from data of temperature and length of day, and in the report for 1944-45 I presented a map of average annual potential evapotranspiration in southwestern United States. The method has been adopted by the Mexican Irrigation Commission, and Ing. Garcia Quintero has made a map of irrigation-water needs of the Republic. The observations used in deriving the formula were all made in the United States, most of them in the West, and we have been uncertain of the possibility of extrapolating into the tropics where temperatures are high and do not vary much from summer to winter. Accordingly, the Mexican Irrigation Commission is embarking on a program to determine experimentally the potential evapotranspiration in several different localities. A modification of the soil-tank method, used by Lee, Debler, Young and Blaney, and numerous other investigators is being employed. The following recommendations were made for consideration in the program:

(1) A well-mixed sandy loam having a moisture equivalent about 18 per cent and wilting percentage about eight should be used in all locations. The soil should be selected in advance and a sufficient quantity collected and mixed to fill all tanks in every location. The soil must be permeable to allow rapid drainage during rain. The surface area of the soil in the tank should be at least four sq m.

(2) The depth of ground water most satisfactory for plants is approximately 50 cm. At greater depths the plants are deprived of needed water, and at lesser depths evaporation becomes excessive and plant roots are restricted.

(3) Daily determinations of soil moisture in the tanks should be made. The determination can be made most conveniently, simply, and inexpensively with the Slater gravimetric plug. The most representative depth in the soil for making the determinations is 15 cm.

(4) The physical constants of the soil (moisture equivalent and wilting percentage) should be determined.

(5) There should be more than one tank of each kind in each locality. Three of each is a minimum for determining the magnitude of individual differences.

(6) The same type of vegetation should be used in every locality. Some native grasses that are widely distributed will serve. Salt grass is recommended.

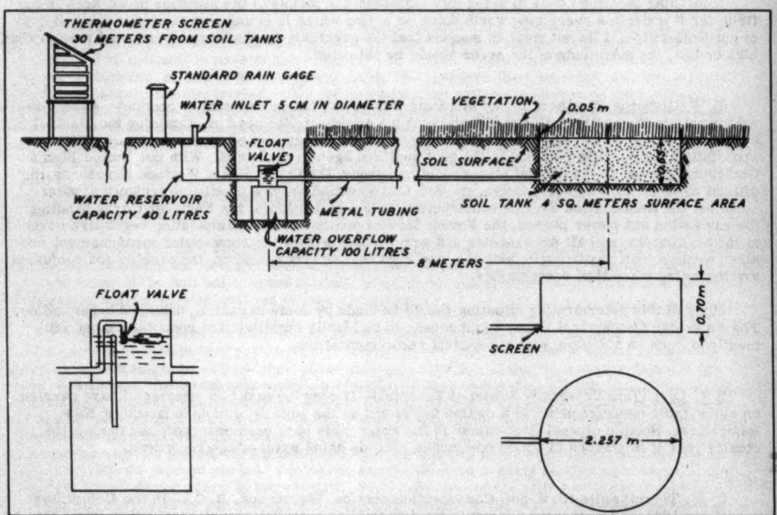
THERMOMETER SCREEN
30 METERS FROM SOIL TANKS
STANDARD RAIN GAGE
WATER INLET 5 CM IN DIAMETER
VEGETATION
0.05 m
FLOAT VALVE
SOIL SURFACE
0.60
WATER RESERVOIR CAPACITY 40 LITRES
METAL TUBING
SOIL TANK 4 SQ. METERS SURFACE AREA
WATER OVERFLOW CAPACITY 100 LITRES
8 METERS
FLOAT VALVE
0.70 m
SCREEN
2.257 m

Fig. 1--Standard installation for determining potential evapotranspiration

(7) It is of utmost importance that exposure to sun and atmosphere be as nearly natural as possible. The water reservoir and water-control equipment should be below ground at least eight m from the soil tank. The thermometer shelter should be 30 m away. The vegetation should cover a considerable area around the soil tanks.

(8) Occasional cutting of the vegetation is desirable. Cutting should not be too frequent nor too near the ground, as the plant roots will be damaged and transpiration arrested. The dry weight of the crop should be determined.

(9) At the end of the experiment studies should be made to determine penetration and ramification of roots through the soil.

(10) At each evaporation station meteorological observations will be needed. The minimum requirements are daily observations of maximum and minimum temperature and of precipitation.

(11) Reliable information on rates of potential evapotranspiration is needed in various parts of Mexico. A minimum study would include five stations, located as follows: (1) The valley of Mexico, perhaps at Chapingo; (2) southern Vera Cruz; (3) the Pacific coastal area of Guerrero or Oaxaca; (4) the valley of the Lerma, perhaps near Celaya; and (5) the northern desert area, perhaps at Torreon.

The problem is more difficult in many parts of Mexico than in southwestern United States, because rainfall during the summer months is often large. For this reason, permeable soil must be used, and provision must be made to catch and measure the excess water. A sketch of the standard installation is given in Figure 1.

H. G. Wilm (Rocky Mountain Forest and Range Experiment Station)--Because our work in the Committee's field has again been very restricted, this summary of research does not cover progress during the past year, but reports informally on an earlier study which was not completed and which we hope to renew in the near future.

In the spring of 1940 an experiment was started at the Fraser Experimental Forest for the purpose of estimating rates of evaporation from snow and of testing practical methods for sampling this important component of the water cycle. Because of limited facilities and the advent of the War, these objectives were only partially achieved. Several portable pans were tried out, and estimates of evaporation were obtained for four successive winter and spring periods.

The study was conducted at an elevation of 9000 ft in the St. Louis Creek watershed, tributary to the Colorado River. In this valley, as elsewhere in the high Rockies, the winters are long and cold, with sustained low temperatures and little or no runoff from snow melt until about March or later. The annual precipitation is about 24 in, of which more than half generally falls during the winter, depositing a three- to five-foot blanket of snow. At the site of the study the average wind movement during the winter and spring has been only about 1-1/2 mi/hr.

The area selected for the evaporation study is a level, natural opening about 1/4 acre in size, thinly fringed by lodgepole pine, Engelmann spruce, and alpine fir trees 20 to 60 ft high.

In this area both "volumetric" and weighing pans were studied. The former consisted of rimmed, circular metal surfaces of several sizes, ranging from 20 to 500 sq ft (see Fig. 2). For these pans, the accumulation of winter and spring precipitation was measured during each of the four seasons by means of shielded non-recording rain gages and a recording gage, and by intensive sampling of snow depths and water equivalents (see Fig. 3). Snow-melt water was conducted to collector cans in a covered, concrete-lined pit.

Three sizes of weighing pan were tested; one, two, and four sq ft in area. Each consisted of a circular, aluminum-painted metal pan six in deep including a transparent pyralin rim about one inch high (see Fig. 4). In operation, an undisturbed core of snow was cut and suspended in the pan on a perforated plate one inch above the bottom of the pan; the top of the core was flush with the pan rim. The pans were filled each morning, weighed, immersed in the snow blanket near the 500-square-foot volumetric pan (see Fig. 5), and weighed again in the evening and morning. Data were obtained only in the spring snow-melt periods of 1940, 1941, and 1942.

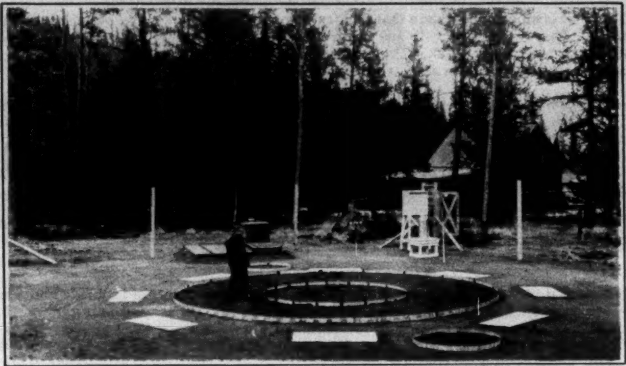

Fig. 2--Snow-evaporation station before completion (1939), showing pans 20 and 500 sq ft in area. The ring inside the large pan divides it into two areas of 100 and 400 sq ft, the snow water from which is collected and measured separately (another 100-square-foot pan and four shielded snow gages were added later)

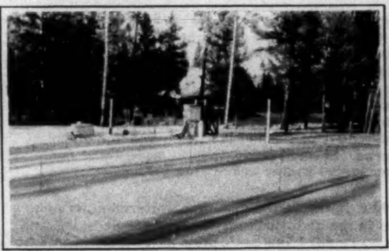

Fig. 3--Snow-evaporation station in March, 1940, showing a level 22-inch layer of snow on the pans (note calibrated snow-depth rods, weather station, and chimney-type entrance to collector pit)

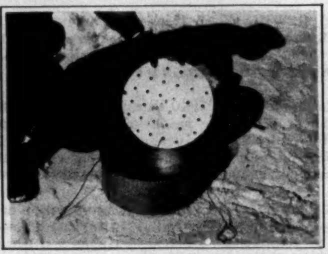

Fig. 4--Weighing-type snow-evaporation pan, one sq ft in area (in use, the snow core is supported on the perforated plate)

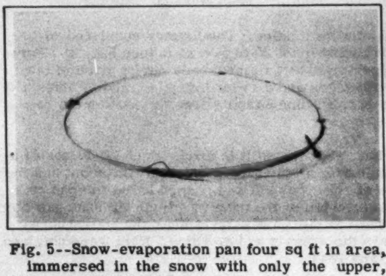

Fig. 5--Snow-evaporation pan four sq ft in area, immersed in the snow with only the upper, pyralin edge exposed

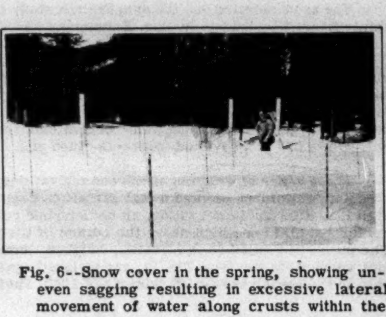

Fig. 6--Snow cover in the spring, showing uneven sagging resulting in excessive lateral movement of water along crusts within the snow column

Accessory equipment included anemometers, maximum and minimum thermometers, and an air thermograph.

The results of these experiments are summarized partially and briefly below:

Volumetric pans--For the four-year period, the 500-square-foot pan indicated an average annual evaporation of 2.23 in. Of this total, only 0.24 in was measured from the first autumn accumulation of snow until melting began in the spring. Starting at that time, spring evaporation averaged 1.99 in, but varied in individual years from 1.33 to 2.75 in.

None of the volumetric pans agreed well with each other as to total seasonal evaporation, and short-term values (as five-day periods) were too inaccurate to be usable. It is believed that these discrepancies are due to several causes, including the following: (a) Errors and instrumental bias in sampling winter precipitation, even with shielded snow gages in a relatively sheltered area; (b) errors and perhaps some instrumental bias in sampling the water equivalent of snow by means of any form of snow tube; (c) lateral movement of melt water above semi-impervious crusts within the snow blanket, so that the real area contributing water to the collector cans may be quite different from the pan area.

Of these components of error and bias, the first two should not necessarily be taken as a reflection on standard methods of sampling precipitation and stored snow. For ordinary purposes their accuracy may be entirely adequate; but the measurement of snow evaporation amounting to only a few hundredths of an inch of water per day requires unusually high standards of precision. At least a part of the solution will lie in greatly intensified snow sampling as compared to our past procedures. The third of these components may often be important because of variable sagging of snow crusts even where the ground and winter snow surface are level (see Figs. 3 and 6).

When calculated by five-day periods, runoff from melting snow on the largest volumetric pan was highly correlated with the number of degree-hours above freezing for each period ($r = + 0.968$).

Weighing pans--In 1940 and 1941, the pans studied were one and four sq ft in area. These differed a good deal in results: in the spring of 1941 the smaller pans indicated 0.55 in of evaporation for the study period, and the larger ones only 0.36 in. After 1941 we abandoned the large pans because of their great weight (over 60 pounds) and unwieldiness when loaded with spring snow, and because of difficulties experienced in cutting and installing such large snow cores. In 1942 the small pans were compared with pans of intermediate size, two sq ft in area. Both sizes gave practically identical total values for evaporation; 1.004 and 1.029 in.

On a relative basis at least, these weighing pans are quite accurate and consistent in their results; replicated pans of the same size agree closely with each other (standard deviation = 0.023 in/wk.)

The total values for spring evaporation from the weighing pans are smaller than those indicated by the largest volumetric pan. A complete comparison is not available, however, as some records for the weighing pans were lost during stormy periods and close to the end of the snow-melt period, when the snow on the ground was too shallow and wet for satisfactory use of the small pans.

After 1942 the snow-evaporation records had to be reduced to the barest minimum, and they were temporarily discontinued after 1943. As indicated by the above statement, the studies are by no means completed; we have only established a good basis for their redevelopment.

Acknowledgment is made to C. H. Niederhof and E. G. Dunford, both of whom conducted these studies and prepared progress reports on them while they were on the staff of the Rocky Mountain Station. Those who are interested in water requirements and consumptive uses of water should find the following bulletin by Harry F. Blaney and Wayne D. Criddle decidedly worth reading: "A method of estimating water requirements in irrigated areas from climatological data," Division of Irrigation, Soil Conservation Service (mimeographed) (provisional), 1945.

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REPORT OF COMMITTEE ON INFILTRATION, 1945-46

G. W. Musgrave, Chairman

The personnel of the Committee and the affiliations with the six Subcommittees is as follows:

Infiltration and the Physics of Soil Moisture and of the Infiltration Process; B. T. Shaw, Chairman, Willard Gardner, S. J. Richards, and F. L. Duley.

Infiltration in Relation to Ground Water; Walter N. White, Chairman, S. W. Lohman, and Samuel F. Turner.

Infiltration in Relation to Snow and Its Physical Properties; Walter T. Wilson, Chairman, B. T. Shaw, and George D. Clyde.

Infiltration in Relation to Surface Runoff; Howard L. Cook, Chairman, W. W. Horner, R. A. Hertzler, G. A. Hathaway, and W. B. Langbein.

Infiltration in Relation to Irrigation; M. R. Lewis, Chairman, Harry F. Blaney, and Howard L. Cook.

Infiltration in Relation to Evapo-transpiration and the Consumptive Use of Water; Harry F. Blaney, Chairman, Walter N. White, Colin A. Taylor, L. K. Sherman, and José Garcia Montes.

The need for clarification of concepts on infiltration in relation to runoff--In the early phases of the development of a new concept, it is common to find considerable diversity of thought among the workers in that field. Subsequently, through the exchange of ideas, and particularly through the development of factual evidence, abstract ideas are crystallized into specific entities. Progress in the development of the field is increased, and practical application of ideas that originally were abstract now proceeds with greater and greater success.

The concept of infiltration as a factor modifying runoff phenomena is still relatively new. Discussions quite diverse in their conclusions abound in the literature. Is it not true that at least some of the diversity of thought is due to diverse interpretations of terms and definitions? Indeed, it would seem that there is need for re-examination of some of the very fundamentals of the problem.

Many have realized during the past several years that there is great need for clarification of thought in this relatively new phase of hydrology. Many have realized that whatever may be done to promote thinking and expression in terms that are specific and are understood by all other workers is certain to result in improved research and improved application of research findings.

The Chairman desires to direct attention to a paper by Chairman Cook of the Subcommittee on Infiltration in Relation to Surface Runoff that appears below. This paper should do much in the way of promoting unanimity in use of terms, of opinion as to their significance, and of clarity of concept. It is believed that this paper, together with the subsequent discussions of it, may be particularly helpful in furthering these objectives.

THE INFILTRATION APPROACH TO THE CALCULATION OF SURFACE RUNOFF

Howard L. Cook

Introduction--Some future historian of the development of scientific hydrology will probably be tempted to call the present period the "era of infiltration." At any rate, the preoccupation of contemporary hydrologists with "the infiltration theory of runoff," and the vast amount of energy they have expended in an effort to turn this concept to practical account, will certainly be put down as a distinctive feature of our times.

There have, of course, been logical reasons for this remarkable interest in the subject. As in all sciences, many have been attracted to it simply because of its newness. Another class--and the one that has participated most eagerly--is composed of those intrepid practicing engineers who are obliged to make the runoff estimates upon which depend the failure or success of costly flood control, water supply, and similar works. Still another group has been intrigued by a purely scientific interest, sharpened by the fact that the calculation of runoff is the central problem of the science of hydrology and involves all phases of the hydrologic cycle. Among these are scientists in the fields of soils, plants, and meteorology. As a result of these various motivations, vast amounts of labor have been expended--much of it misdirected--and many exaggerated claims have been made, to be countered, naturally, by the disparaging murmurs of the "old guard," and other important lines of investigation have been temporarily slighted. But real progress has been made. Better estimates of runoff are now possible than could be made previously. Problems that would not yield at all to earlier methods are now soluble, albeit the solutions are sometimes only rough approximations. The inescapable conclusion is that a tool of considerable practical value has been added to the equipment of the hydrologist.

Clear as it is that progress has been made, it is even more obvious that the infiltration approach is still in its infancy. It cannot yet be applied in the routine manner of the fully-developed technical procedure. Nearly every application still requires laborious analyses of basic data, and in many instances judgment must be substituted for scientific knowledge. Added to all this, further progress is inhibited by confusion in definitions, obscurity in basic concepts, and an amazing paucity of published data.

The time has come to take stock of what has been done and to formulate the problems that impede progress. The primary objectives of this paper will be, therefore, to examine critically the procedures that have been devised, to clarify the concepts and principles upon which further progress must be based, and to outline the principal problems that must be solved.

As the title indicates, consideration is limited to the calculation of surface runoff--the fraction of the total runoff controlled by infiltration--and attention is confined to water applied to the soil as rainfall. The paper excludes any discussion of infiltration as a physical process. The principal terms and symbols used in this paper are defined as follows:

Infiltration--The passage of water through the surface of the soil into the soil mass

f--Infiltration rate (usually expressed in in/hr)

f_p--Infiltration capacity or potential infiltration rate, that is, the rate at which infiltration would take place at any instant were the supply to equal or exceed this capacity

f_{av}--Average infiltration rate, that is, the average rate of infiltration during a period in which water (rainfall only) is applied at a rate equalling or exceeding f_p

The ϕ index--The rate of rainfall over and above which the volume of rainfall equals the volume of runoff

The W index--An index for a multiple-complex area derived in the same way as f_{av} is determined for a single complex

The W_{min} index--The value of W for a rain occurring after the area has been thoroughly wetted and infiltration capacities thus reduced to minimum values

S_e--Effective surface storage, that is, the depth of water that would have run off were it not for the existence of surface storage. This is made up of water trapped in depressions plus that infiltrated out of water in transit.

q_s--Rate of surface runoff, that is, the rate at which surface runoff is passing from a given area at any instant

i--Rainfall intensity, here used as the intensity of "ground rainfall," or the rate at which water is reaching the soil at any instant

P_s--Supra-rain, the depth of rainfall represented by the area of the intensity-time graph over and above any selected intensity. This has previously been called "excess rainfall," a thoroughly satisfactory term, but one whose value has been destroyed by also applying it to the difference between rainfall intensity and infiltration rate, an entirely different quantity. Some have even equated these two unlike quantities. The resulting confusion has greatly hindered progress.

Storm period--A period during which the precipitation attributable to a single atmospheric disturbance takes place. A storm period is usually made up of several rain periods.

Rain period--A period in which rainfall does not cease for more than one hr, thus a period of substantially continuous rainfall

Complex--A combination of soil, cover, and condition for which an infiltration curve may be constructed

Surface and subsurface runoff--The runoff from an area is the water flowing from it over the surface of the Earth, either in streams or as overland flow. Part of this water has never been below the surface. This is called surface runoff. Another part has previously passed into the Earth and subsequently returned to the surface. This is called subsurface runoff. A normal stream carries both surface and subsurface flow in proportions varying widely from time to time. During floods most of the water discharged from deep-soiled drainage basins is ordinarily made up of surface runoff. However, in areas of low storage capacity (such as thin-soiled basins) a large proportion of the flood water may consist of subsurface runoff. During long dry periods, too, most of the stream flow is derived from underground sources.

It is desirable to take up subsurface flow at the very outset, because three important points need to be understood before infiltration can be intelligently discussed. These are: (1) Only surface runoff can be directly determined from infiltration data. (2) When runoff contains subsurface flow, the gaged discharge cannot be used to derive infiltration data for the area unless the surface runoff can be separated from the total. (3) In general, there is no way of separating surface and subsurface runoff when only records of the rates of flow are available.

The reasons for the first limitation are clear, or at least will be made so by the following discussion of the mechanics of surface runoff.

The second point is also fairly obvious. When a flood record contains subsurface flow, any infiltration rates or indices derived from it will be too small. They will measure, not the capacity of the surface to infiltrate water, but the capacity of the watershed to retain water under the existing conditions. Absurd conclusions have been reached through failure to recognize this. For example, on a thin-soiled watershed in Arkansas, the infiltration indices derived from runoff records indicate that the infiltration capacity of the area during large storms is not more than 0.02 in/hr. The watershed is wooded, and studies with artificial rainfall equipment show that the minimum infiltration capacity of most of the surface exceeds one in/hr. It seems quite probable, therefore, that during the floods analyzed there was little if any surface runoff. The rainfall was being infiltrated, but since it could not be retained in the thin and previously wet soil, it was quickly returned to the channel system to create a flood. It is the analysis of records such as these that has led to the rather widespread notion that under long continuing rains the infiltration capacity of an area approaches zero, even when it has a good cover. Actually, the infiltration rates may remain very high, the controlling factor being the storage capacity of the soils.

The third point, the statement that surface and subsurface flow cannot generally be separated, is set down as a warning against misinterpretation of some so-called "infiltration" data and also against overly optimistic anticipation of what can be accomplished with ordinary stream-flow records. It is true that for the special case when the subsurface flow is derived entirely from the zone below the permanent groundwater table, and no groundwater accretion occurs, a satisfactory estimate of subsurface flow can be made simply by extending the groundwater depletion curve. Another such special case is found when the total subsurface runoff is very small compared to the total surface runoff, for then even large errors in estimating subsurface runoff have an insignificant effect upon derived infiltration data. But when subsurface flow constitutes a relatively large proportion of the total flood, when accretion to ground water occurs, and particularly when transient zones of saturation are set up (as in thin-soiled watersheds), there is no way to identify the source of the water from a simple record of stream flow. To separate surface and subsurface flow under such conditions requires independent measurements of the variables controlling either the surface or subsurface runoff. Such measurements will never be available except for special research projects, and even on experimental areas the data are seldom complete.

The mechanics of surface runoff--When rain begins to fall at intensities exceeding the rate at which it can infiltrate, the following sequence of events is set in motion: (1) A thin layer or film of water is formed on the surface, and down-slope flow is initiated. (2) The flowing water accumulates in depressions on the surface. (3) When these depressions become full, they start to run over. (4) The overflow enters micro-channels, which coalesce to form rills, the rills combine to form rivulets, these discharge into small gullies, and this process is extended until the water is finally discharged into the major drainage channels. (5) Along each collecting channel lateral inflow takes place from the surface of the land.

Before surface runoff starts, and throughout the course of events outlined, water is infiltrating into the soil. The role played by infiltration is graphically depicted by Figure 1 for a continuous rain of a uniform intensity exceeding the capacity of the soil to infiltrate water. To simplify further the example for illustrative purposes, the area involved is assumed to be but a few square feet and to be uniform in soil, cover, and condition.

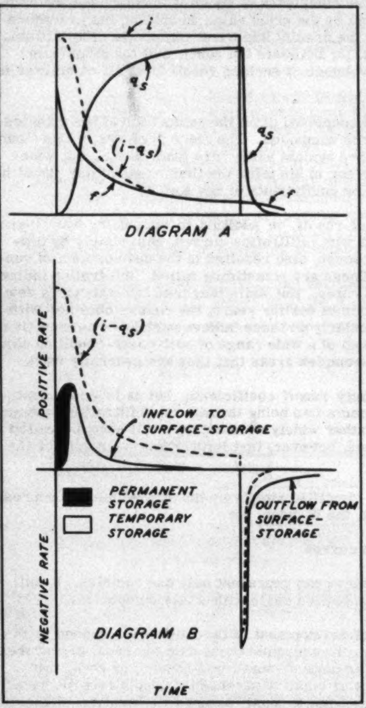

Fig. 1--Characteristic variations of infiltration and storage rates during rainfall of constant intensity

Diagram A of Figure 1 shows that the infiltration rate f begins at a high value, decreasing rapidly during the earlier part of the rain period, and then gradually flattening as the rain continues, almost as though it were approaching a constant value. On this same diagram appears a curve marked $(i - q_s)$. If rainfall continues until the rate of runoff approaches a constant, the retention-rate and the infiltration-rate curves coincide. The cumulative area between these two curves represents the volume of water stored on the surface up to any given instant. Diagram B of Figure 1 shows how this surface storage builds up early in the storm and is disposed of by surface runoff and infiltration after the rain ceases. Also reproduced on B is the $(i - q_s)$ curve of Diagram A.

Figure 1 shows that infiltration is only one of the factors that influences the rate of surface runoff. But it must be appreciated that all of the surface water that does not run off (with the exception of that evaporated from surface storage) is ultimately disposed of by infiltration. Infiltration, then, is the controlling factor in the surface-runoff process. As will be evident from the foregoing discussion, however, it does not necessarily control total runoff, for the latter normally contains subsurface flow.

The problem of calculating surface runoff

The infiltration-curve approach--In order to make a precise calculation of the rate of surface runoff for a given complex, it is necessary, strictly speaking, to reverse the process illustrated by Figure 1, that is, to construct the infiltration-rate curve that would subsist during the given rain and to calculate the rate of inflow to, and outflow from, surface storage throughout and after the rain. In general, it is impossible to compute these elements precisely. It is much easier to make estimates of the total surface runoff that would occur during a rain. As a matter of fact, the exact rate at which the runoff leaves any elementary portion of a watershed is rarely of practical interest, since the hydrograph of runoff from a small area will be quickly changed beyond all recognition, as, in passing through the channel system, it is altered and smoothed by storage and by combination with the flood waves from the countless other segments of the basin.

Another point that will be clear if Figure 1 is thoroughly understood is that surface runoff can be precisely calculated only for an area throughout which the following factors are invariable:

(a) Amount and intensity of rain; (b) infiltration characteristics; and (c) surface-storage characteristics. The second requirement means that the area must be homogeneous with respect to soil, vegetal cover, and surface condition or treatment, for these are the factors that control infiltration. Such a homogeneous combination is here called a soil-cover-condition complex, or in the interest of brevity, simply a complex. For all practical purposes this restricts the applicability of infiltration curves to relatively small segments of a drainage basin, it being well known that soil, cover, and condition vary greatly over areas of any size.

Surface-storage characteristics are governed by the same factors that control infiltration--soil, cover, and condition--plus the factor of slope.

From what has been said, it is apparent that infiltration data can be used in a rational manner only in calculating surface runoff from relatively small, physically homogeneous areas. This means that the surface runoff from a large complicated watershed can be estimated rationally only by separately calculating the runoff from the various complexes of which it is composed and combining these to obtain the total surface runoff caused by the given rain. In outline, the procedure is: (1) Determine the areas and locations of all of the areally important complexes of the basin. (2) Develop infiltration data for each such complex. (3) Estimate the runoff that the given rain would produce on each complex. (4) Combine the volumes of surface runoff from all complexes to obtain the total volume from the entire area.

The runoff from a watershed should always be conceived of as the summation of the volumes of runoff from the individual complexes of which it is composed. The mere presence of this "summation concept" in the mind of the technician insures against some very fundamental, but widespread, errors in reasoning. Moreover, it keeps clear in his mind the limitations of any result he may obtain by the use of multiple-complex indices or coefficients of any sort.

The index approach--The infiltration theory of runoff, in addition to presenting hydrologists a truly rational means of calculating surface runoff with infiltration curves, has, simply by providing a physically correct concept of the runoff process, also resulted in the development of runoff coefficients superior to those formerly used. These are sometimes called "infiltration indices" and have even been presented as actual infiltration rates. But while they take into account a few more factors than the primitive runoff-rainfall ratios of earlier years, the results obtained with such coefficients are essentially empirical. Particularly do these indices partake of an empirical nature when they are derived for watersheds made up of a wide range of soil-cover-condition complexes, and it is in dealing with just such multiple-complex areas that they are generally used.

Indices of this type are, strictly speaking, simply runoff coefficients, but it is convenient to have a class name for them. Inasmuch as they came into being through the infiltration concept of runoff, and because the term has already been rather widely utilized, they will here be called "infiltration indices." It is to be clearly understood, however, that infiltration is but one of the factors that enter into such indices.

Particular kinds of infiltration indices will be identified simply by the symbol used to represent them. Thus, reference will be made to the ϕ index, the W index, etc.

Infiltration curves

It has already been shown that an infiltration curve can represent only one complex. It will be understood, therefore, that the remainder of this section deals with single complexes.

Assembly of basic data--At the present state of development of the infiltration method it is nearly always necessary to begin with the raw data. To assemble these data the usual procedures are to: (a) Analyze records of rainfall and runoff for plots or small watersheds, or both, that have been in operation for some time; (b) gage plots or small watersheds if usable records have not already been collected; and (c) apply artificial rainfall to small plots representative of the various complexes for which infiltration curves are required. Sometimes a combination of these methods is utilized.

The many difficult problems encountered in obtaining the necessary basic data will not be dealt with in this paper.

Derivation of infiltration rates--The first problem that arises in the construction of infiltration curves is the derivation of infiltration rates. This is difficult, because infiltration must be measured indirectly by gaging rainfall and runoff. Even when precise records of these latter variables are available, the derived infiltration rates are necessarily approximate, for unless the rate of runoff is constant, the volume of water stored on the surface changes constantly. Even for a very small area, therefore, the difference between the rainfall intensity and the runoff rate at any instant represents the infiltration rate only when corrected for the rate of change in surface storage. Because surface storage corrections can only be approximated, the values of the derived infiltration rates are themselves approximate.

The two ways in which data for infiltration curves are derived may be outlined thus:

(1) When time of transit can be neglected--On very small areas (plots) subject to uniform rainfall at rates exceeding the infiltration rate, the difference between the intensity of rainfall and the rate of surface runoff is a first approximation to the infiltration rate at any instant, becoming exactly equal to the latter when the rate of runoff becomes and remains constant (see Fig. 1). Even for the interval during which the runoff rate is changing, corrections can be made [see "References" at end of paper, HORTON, 1939] for the effect of surface storage, and rather close approximations to the actual infiltration rates obtained. At the present time this approach is virtually limited to the analysis of results obtained with artificial rainfall equipment, since natural rainfall seldom occurs at rates sufficiently uniform to permit analysis with existing tools.

(2) When time of transit cannot be neglected--On larger areas (small watersheds) the time required for the water to pass from the point at which it falls to the outlet is so great that the differences between rates of rainfall and runoff do not constitute even a first approximation to infiltration rates. Moreover, without continuous independent measurements of surface storage--and except in special research projects it is impractical to even approximate such measurements--there is no way of correcting for the rate of change in storage. To derive infiltration curves from small-watershed records, therefore, the usual procedure is to select storms made up of several rain periods and to estimate the average infiltration rate during each period, that is, to derive for each rain period the value of f_{av} discussed hereinafter. The values are then used to construct standard curves by methods to be discussed subsequently.

Nothing further need be said of the derivation of infiltration rates by the first method. However, the calculation of f_{av} values calls for a further explanation.

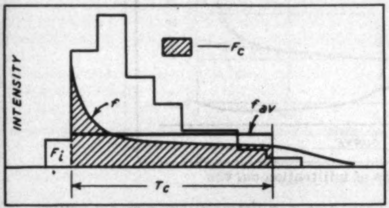

Fig. 2--Diagram illustrating derivation and meaning of f_{av}

The value of f_{av} is illustrated by Figure 2 and derived by the following procedure: (1) The total infiltration F_c that occurred during the time rainfall intensity exceeded the infiltration capacity is determined by the expression

$$F_c = P - (Y_s + S_e + F_i) \ldots\ldots (1)$$

in which P = rainfall causing the runoff, Y_s = surface runoff attributable to the given rainfall, S_e = effective surface storage (usually estimated), and F_i = infiltration that occurred before rainfall intensity exceeded infiltration rate (usually estimated). (2) The time T_c during which infiltration occurred at capacity rates is estimated (usually upon the assumption that this interval begins when the rainfall intensity exceeds the infiltration rate and ends when the temporary surface storage is exhausted). (3) The value of f_{av} is obtained by dividing F_c by T_c.

Kinds of infiltration curves--There are three kinds of infiltration curves: (1) Infiltration-rate curves (f curves), showing the actual rate of infiltration during a particular storm; (2) infiltration-capacity curves (f_p curves), showing what the infiltration rate would be at any instant during a specific storm if the rainfall intensity were to equal or exceed the infiltration capacity at that instant; and (3) standard infiltration-capacity curves (standard f_p curves), showing what the rate of infiltration would be under a standard rain throughout which the rainfall intensity continuously exceeded the infiltration rate.

The three kinds of curves defined above are illustrated by Figure 3. Obviously, infiltration-rate and infiltration-capacity curves can only be used for storms exactly like those for which they were derived. Standard curves, however, can usually be employed to construct fair approximations to the f and f_p curves for any storm. Moreover, only by converting the data to some standard form

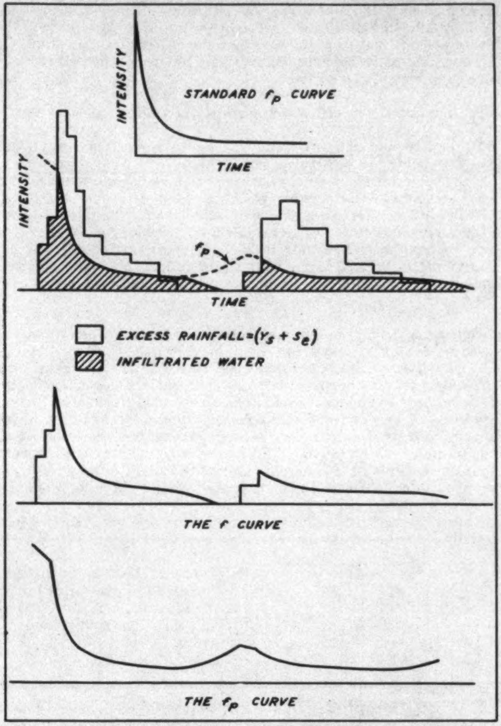

Fig. 3--The three kinds of infiltration curves

may a comparison be made of the infiltration characteristics of different soil-cover-condition complexes.

The shape of standard f_p curves--The studies that have been made to date indicate that the relative shapes of standard infiltration curves for different complexes vary widely. Some idea of this variation is afforded by Figure 4, but it has also been found that the variations in the shapes of the curves obtained for a given complex at different times of the year and under different antecedent conditions are not ordinarily large enough to preclude the use of a single curve shape for that complex, considering the other sources of error to which the infiltration approach is subject. This does not mean that the curve used for a wet condition has the same relative shape in its entirety as the curve for dry conditions. The assumption is, rather, that in passing from one given value of f_p to a lower given value the curve will follow the same path. It has, at any rate, become fairly standard practice to construct one standard curve and use different segments thereof for different antecedent conditions.

There is evidence that a justifiable improvement in results can be attained by constructing different standard f_p curves for the growing and the dormant seasons. Whether or not it is advisable to alter the curve shapes with season and with other factors will not long remain in doubt as the knowledge gained with experience accumulates.

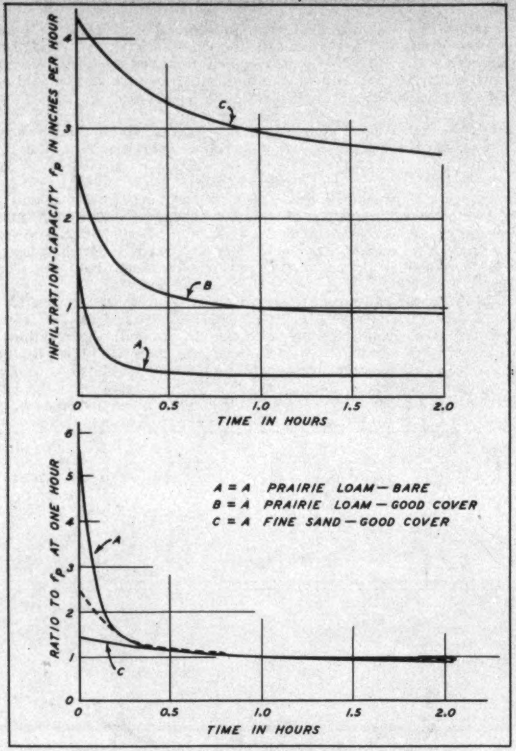

Fig. 4--Some standard infiltration-capacity curves illustrating variations in shape

HORTON [1939] has fitted a wide variety of infiltration curves with the equation

$$f = f_c + (f_o - f_c)e^{-K_f t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which f_c = the constant value of f which the curve approaches as t increases, f_o = the value of f for t = 0 (initial value), K_f = a constant, t = time, and e = base of natural logarithms (2.718 . . .).

This equation can be used to represent standard f_p curves. One advantage of finding the equations of such curves is that the constants can be published in lieu of tabulations or of reproductions of the curves themselves, thus greatly reducing the space required for their presentation. Another advantage of obtaining parameters such as f_o, f_c, and K_f is that they may be related to known physical characteristics of the complexes for which the curves were obtained. It will be evident that this greatly simplifies the study of the variation of infiltration characteristics with physical factors. It is also possible that such relations may eventually prove of considerable practical value in predicting the infiltration characteristics of complexes for which no experimental data have been obtained.

Construction of standard f_p curves--The first step in the preparation of standard f_p curves is the selection of the conditions to be considered standard. The specification of these conditions may, of course, be varied to suit the particular use to be made of the curves. As an example, the following conditions are often specified for curves derived from artificial rainfall tests: Antecedent wetness, thoroughly wetted 24 hr previously; season, growing; and condition, the usual summertime condition, not recently cultivated and at least one in of rain since the last cultivation, not abnormally trampled or otherwise compacted.

In some studies separate standard curves are also constructed for the dormant season; in others, the standard curve for the growing season is simply corrected for use in the dormant season.

A standardized curve will, of course, give precise results only for the conditions for which it has been devised. To calculate surface runoff for other conditions, corrections must either be made to the curve itself or to the runoff calculated by its use. Fortunately, however, in many undertakings it is sufficient to determine the runoff that will occur under the adopted standard conditions. When this is possible, the calculations are greatly simplified.

The construction of standard f_p curves from data secured with artificial rainfall equipment is comparatively simple, and if the spray applied truly simulates natural rainfall, that is, if the size and velocities of the drops are about the same as for natural rainfall, the resulting curves can often be applied directly in the calculation of surface runoff. HORTON [1940] has proposed a method for correcting infiltration data obtained with sprays differing from natural rainfall. The derivation of infiltration rates from artificial rainfall data has already been discussed. If the conditions for the test were standard, the values of f thus determined need only be plotted against time to obtain a standard f_p curve. Naturally, measurements are always made on several plots,

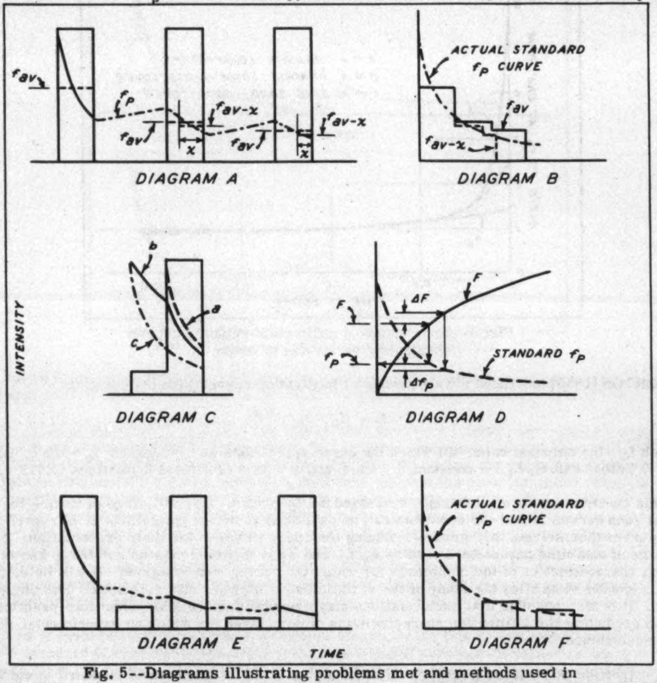

Fig. 5--Diagrams illustrating problems met and methods used in deriving standard infiltration-capacity curves and the final curve for each complex is constructed after considering the curves for all of the sample plots representing that complex.

It is much more difficult to develop standard f_p curves from small watershed data. The usual method of dealing with such data is to estimate the average infiltration rates (f_{av} values) for the various runoff-producing showers that make up a storm. These values represent the average ordinates of arcs of the infiltration-capacity curve. On the time scale each such arc occupies the interval of time during which the runoff-producing rain occurs. When several runoff-producing rain periods occur during a single storm, a value of f_{av} may be estimated for each period and a standard curve approximated by replotting these values on a time scale at the times they would have occurred had the rain been continuous. This has been called "compacting" or "condensing" the f_{av} values.

Diagram A of Figure 5 shows a very simple storm consisting of three periods of uniform rain at an intensity exceeding the maximum ordinate of the assumed standard f_p curve. There has been placed on the diagram a curve showing the variation of f_p throughout the storm. In doing this the "recovery" of f_p between rain periods has been considerably exaggerated to bring out better one of the problems involved. Also the assumption has been made that the f_p curve will not change in shape with time, that is, that when intensity exceeds infiltration rate, all arcs of the curve between specified values of f_p will be identical. There are also shown on this Diagram the values of f_{av} that would be found for each rain period if the infiltration capacity actually varied as indicated. The interval marked X during each rain period shows the portion of the arc of the standard f_p curve that has not been previously operative, and the values marked f_{av-x} represent the average value of f during these intervals.

Since, on Diagram A, no rain occurs between the rain periods, the obvious way to condense the f_p curve is simply to plot the f_{av} values adjacent to each other in the manner indicated on Diagram B. If a curve is placed through these mean ordinates, a first approximation to the standard curve is obtained. But Diagram B shows that the plotted values of f_{av} do not give a good fit to the lower end of the actual curve. It is easy to perceive that this is because the arcs of the f_p curve from which the f_{av} values were derived are, in part, composed of arcs used in deriving previous values of f_{av}, that is, these parts of the curve have been used more than once. This is because of the recovery of f_p between rains. In practice this effect of double counting can often be neglected. But if any substantial part of the curve is found to be duplicated because of recovery, an approximate correction can be made by: (1) Using the uncorrected f_{av} values to construct a first approximation to a standard curve; (2) utilizing this to sketch in arcs; and (3) plotting new values of f_{av} for the portions of the arcs not previously operative. This, of course, could be repeated as many times as desired, but it will be found in practice that there are nearly always other errors that make attempts at a high degree of precision a waste of time.

The next major difficulty arises when the runoff-producing rain is preceded by rainfall at intensities less than f_p. This problem is illustrated in a simple form by Diagram C. Several assumptions have been made, at one time or another, about the effect of the initial rain on f_p. Among these are:

(a) The obviously incorrect assumption that the value of f_p does not begin to decrease until the runoff-producing intensities occur. The infiltration curve resulting from this assumption is shown on Diagram C as curve (a).

(b) The assumption that the value of f_p at any instant depends upon the infiltration that has occurred up to that instant, from which it follows that if the actual infiltration during a given time interval constitutes a given fraction Z of the infiltration that would have occurred with intensity exceeding f_p, the decrease in f_p will be Z times the standard decrease, that is, $\Delta f_p(\text{actual}) = Z \cdot \Delta f_p(\text{standard})$, in which $Z = \Delta F / \Delta(\Sigma f_p)$. By the use of a mass curve of the area under the standard curve, in the manner indicated on Diagram D, the variation of f_p during the period of initial rain has been shown on the Diagram C as curve (b). For periods during which f_p exceeds i this method gives a correct answer whether f_p is dependent upon mass infiltration, as assumed here, or upon previous rainfall as hypothesized by HORTON [1940].

(c) The assumption that the infiltration capacity will decrease at the same rate regardless of rain intensity. The curve of f_p resulting from this assumption is the one labeled (c) in Diagram C.

Assumption (b) is preferred at the present time, but considerable research will be needed before the effect of initial rainfall can be accurately predicted.

Another very troublesome problem is illustrated by Diagram E of Figure 5. Here the rains used in Diagram A are reproduced with periods of low-intensity rain between them. One question is--how does the value of f_p vary between runoff-producing showers? Another is--how can the value of f_{av} be condensed in time when such intermediate showers occur? The answer to the first question is obviously furnished by adoption of the assumption made for handling initial rain, that is, assumption (b). But if this hypothesis is accepted, the second question is also answered, because the time interval between two calculated values of f_{av} must then become the total rain falling during the intermediate shower divided by the rate of infiltration during that shower. In other words, the values of f_{av} must be spaced so that the area under the resulting standard f_p curve will equal the infiltration actually occurring during the interval between the runoff-producing showers. Here again, an approach by successive approximations is generally required. A trial f_p curve is sketched in between runoff-producing showers and values taken from this curve to calculate trial-time intervals. The values of f_{av} are then plotted, using these trial intervals, and a trial standard f_p curve sketched. If the values of f_p used in computing the time intervals do not lie close enough to this curve, the process is repeated using the derived curve. Diagram F shows the first trial plotting of f_{av} values for the rain periods of Diagram E. Using a curve drawn through these values, corrections for the double counting effect already discussed may be made if necessary.

The examples used in Figure 5 have been made simple better to illustrate concepts and principles which, if clearly understood, can readily be applied to more complicated situations.

It must be appreciated that in working with small-watershed data, it is practically impossible to derive a good standard curve from the data for one storm. The usual procedure is to derive curves for a large number of storms and to consider all of them in constructing the final standard curve.

A study of the foregoing, and of the diagrams of Figure 5, will indicate the problems encountered in the construction of standard f_p curves from small-watershed data, and will emphasize the need for further research. These problems might be summarized as follows:

(1) Those portions of the standard f_p curve that are steep or sharply curved cannot be defined precisely by f_{av} values, because these values are average ordinates covering rather long intervals of time. These long intervals have the effect of obscuring both the rather sharp curvature of standard f_p curves and the high initial infiltration capacities of many complexes.

(2) The recovery of f_p between rain periods must, in some cases, be taken into account, and at the present time little is known about the rate of recovery.

(3) It is necessary to assume that the shape of the arcs of the standard f_p curve are invariable, that is, that in passing from a given value of f_p to a lower value, the curve will always follow the same path. The applicability and limitations of this assumption need to be checked by further research.

(4) The plotting of f_{av} values must be corrected for intermediate showers. Assumption (b), widely used as a basis for such corrections, must be checked and better procedures developed if it does not yield sufficiently accurate results.

(5) The effect of initial rainfall at intensities less than f_p must be taken into account. At the present time assumption (b) must be used.

(6) It is difficult to determine the values of f_{av} with any high degree of precision. In particular, the corrections made for surface storage are frequently inaccurate, and this materially affects the shape of the standard curves derived from the data. The usual effect is to make the derived curves fall less sharply than they should during the early stages of rainfall.

In addition to more research on the above problems, a great deal of work needs to be done in the comparison of curves prepared by this method and those obtained with artificial rainfall.

In concluding this discussion of infiltration curves, attention is again called to the fact that all such curves are necessarily approximate, and that the degree of approximation depends not only upon the basic data utilized but also upon the method of derivation. It follows that to insure proper use of an infiltration curve its antecedents should always be fully explained.

Infiltration indices

There are as many kinds of infiltration indices as there are procedures for deriving such indices. In general, however, the object of all of these methods is to obtain a coefficient that may be applied to an entire rain period (or sometimes even to an entire storm made up of several rain periods) to arrive at an estimate of the runoff that would be produced by a similar rain. Indices are ordinarily determined from actual measurements of rainfall and runoff on gaged streams.

Three types of indices are in general use: (a) Indices derived by equating supra-rain and runoff. This will here be designated as the ϕ index. (b) Indices supposed to represent the average infiltration rate during a rain period. For a single complex this would be the quantity f_{av}. For a multiple-complex watershed it will be designated for purposes of this paper as the W index. (c) Indices intended to represent the minimum infiltration rate reached after long-continued rainfall. If derived for a multiple-complex area in the same way as the W index, this quantity might be called the W_{min} index.

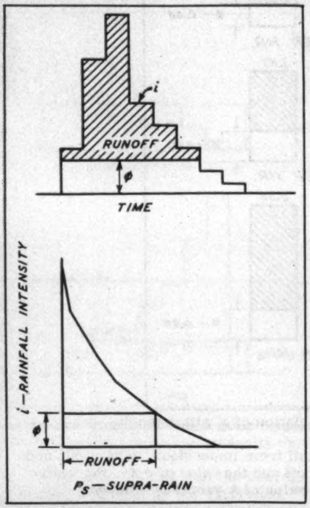

Fig. 6--Diagrams illustrating derivation, meaning, and use of the ϕ index

The ϕ index--This index is simply the rainfall intensity over and above which depth of rain (the supra-rain) equals the surface runoff. Its value can be conveniently derived by constructing a supra-rain curve and entering this curve with the runoff. The procedure is illustrated by Figure 6.

The ϕ index can, of course, be derived either for a single complex or for a complicated watershed containing numerous complexes.

For a single complex the ϕ index represents, as will be clear from an examination of Figure 6, the constant rate at which water would have to be extracted from the rainfall to yield the runoff that actually occurred. The actual extraction takes place, however, at a varying rate and not by infiltration alone, but also by surface storage. Since the value of ϕ represents both the effect of infiltration and storage it might more precisely be called a retention-rate, rather than an infiltration index.

The effect of surface storage upon the value of ϕ may be quite small when the volume of the infiltration is large compared to that of the surface storage. Therefore, when an area of high infiltration capacity is subjected to a long rain, the value of ϕ may be very close to the value of f_{av}. On the other hand, when the surface storage is high relative to the total infiltration the value of ϕ will be considerably greater than f_{av}. This condition most commonly occurs when relatively impermeable areas are subjected to short storms of high intensity.

A further insight into the nature of ϕ can be obtained by considering a hypothetical watershed having a completely impervious surface but a high capacity for surface storage because of the presence of contour furrows, storage terraces, or natural depressions. Were such an area subjected to a heavy rain, a fairly large volume of water, perhaps up to two inches in depth, might be stored upon the surface. It is obvious that although the ϕ value for this event might be quite large, it would reflect only the surface-storage effect and would not be a measure of infiltration.

From the foregoing it will be evident that for a single complex the ϕ index has a readily understandable physical significance. But for a multiple-complex area the meaning of such indices becomes obscure. This may be illustrated by calculating the value of ϕ for a simple hypothetical watershed one-third of which is impervious, one-third cultivated, and one-third in good grass or forest. Assume: (1) That only surface runoff occurs from these complexes; (2) that the watershed is subjected to a series of five simple rains of uniform intensities of 0.2, 0.5, 1.0, 2.0, and 3.0 in/hr, each lasting one hr; and (3) that the infiltration characteristics of the watershed are exactly the same at the time of each storm. In other words, it is assumed that every variable operated in exactly the same way during each storm except the variable of intensity. The five storms are shown graphically on Figure 7.

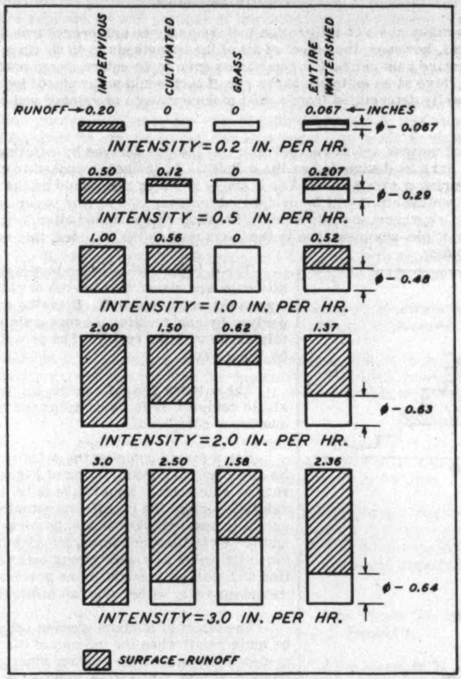

Fig. 7--Simple illustration of reason for variation of ϕ with intensity

For each rain the first three blocks represent the runoff from impervious, cultivated, and grassed areas, respectively. The last block shows the runoff and the value of ϕ for the entire watershed. An examination of the chart will show that the value of ϕ varies as follows:

Intensity in/hr	ϕ in/hr
0.2	0.133
0.5	0.293
1.0	0.48
2.0	0.63
3.0	0.64

It will be noted that as the intensity of the rain increases, the value of ϕ increases and approaches a constant. This is because the higher the intensity the greater the proportion of the area producing runoff throughout the rain, not because infiltration capacity increases with intensity of rainfall.

The value of ϕ is also affected by the rainfall-intensity pattern. This is illustrated by Figure 8, upon which are shown three rains of the same volume and identical intensities, but with these intensities distributed differently in time. The runoff for each was calculated holding constant every variable except the pattern, and assuming that during periods when f_p exceeds i, the former varies in accordance with assumption (b) discussed previously. The resulting values of ϕ are tabulated below:

Pattern	ϕ in/hr
A	0.40
B	0.50
C	0.35

In short rains of higher intensity the variation would be even greater.

The f_{av} and W indices--The W index is obtained for a multiple-complex watershed in the same way as f_{av} is derived for a single complex (see "Derivation of infiltration rates" and Fig. 2). It is apparent that this index and f_{av} became one and the same quantity for a single complex. But while f_{av} has a real and explainable physical significance, a similarly derived multiple-complex index, as will be shown later, does not. For this reason it is wise to use a different symbol for the latter.

The quantity f_{av} is usually calculated in the course of preparing standard infiltration-capacity curves and is not often used as an index. The W index is rather widely utilized for large watersheds, sometimes under the impression that it represents an actual infiltration rate.

It was previously made clear that f_{av} represents the average ordinate of an arc of the infiltration-capacity curve. The cardinal difficulty in using the value of f_{av} as an index is that except for special cases it is not possible to tell which portion of the curve the derived value of f_{av} represents. One such special case is found when the rainfall begins at a high intensity exceeding the infiltration rate. The value of f_{av} then represents the average ordinate of the infiltration-capacity curve for the given condition from zero time to time T_c. Another is encountered when long-continued rain previous to the period analyzed has reduced the infiltration rate to practically a constant. The value of f_{av} then represents the average ordinate under a segment of the standard infiltration curve where it approaches or has reached a sensibly constant value.

The W index has no more real physical significance than the ϕ index has for a multiple-complex watershed, and for the same reasons.

The W_{min} index--W_{min} is the W index for extremely wet conditions. It is usually calculated for the last rain period in a long-continued storm made up of a number of rain periods and is used in estimating maximum flood possibilities. It will be found that for such extreme conditions the values of ϕ and W_{min} are almost identical.

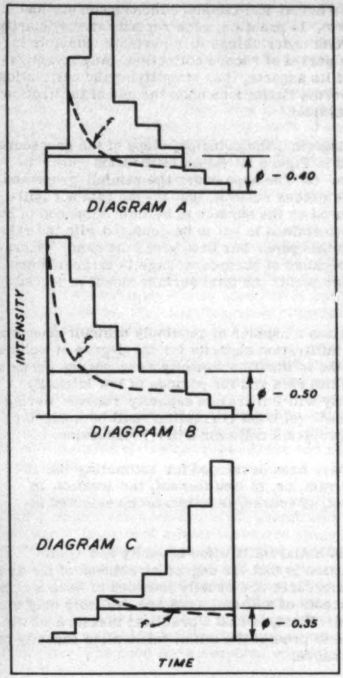

Fig. 8--Diagrams illustrating effect of time distribution of intensity on ϕ

This index approaches the average (weighted by area) of the minimum infiltration rates for all complexes making up the watershed. This is because for extreme flood-producing conditions all parts of the basin are very likely to be producing runoff.

It has already been stated that for such extreme conditions the values of W_{min} and ϕ approach numerical equality.

Identification of indices--In view of the wide variety of indices in use, of the even wider diversity of methods used in deriving them, and of the lack of standard symbols, all indices should be clearly identified. In the present state of development of the methodology the only safe way to identify an index is to describe the procedure by which it was derived.

The use of infiltration curves

In the use of infiltration curves, the nature of the problem and the kind of data available determine the procedure. The most difficult situation arises when no independent measurements have been made of conditions existing prior to a given storm, and it is required to estimate the amount of runoff that would be produced by that particular storm under the actual conditions existing at the time. But not all problems met in practice are so complicated. A very common special problem that can be solved with comparative ease is that encountered in estimating maximum flood runoff. The simplifying assumption here is that the area has been thoroughly wetted by previous rains. This makes it possible to use, without correction, infiltration curves obtained for wet conditions. Another special situation arises where actual soil moisture measurements and condition observations have been made before the storm. In practice, such records are ordinarily only obtainable for experimental areas. But in important undertakings it is perfectly possible to obtain such measurements by prefacing the study by a period of record collection. Any investigation, then, can be reduced to a special case in some of its aspects, thus simplifying the calculations and enhancing the precision of the results. In other words, limitations upon the use of infiltration curves are, to a large extent, economic rather than physical.

In all applications of infiltration curves to rain diagrams, the principal steps of the procedure are the same. They are outlined below and illustrated in Figure 3. (1) An infiltration curve is drawn upon the intensity-time graph for the given rain. (2) The area under the rainfall graph and above the infiltration curve is determined. This is the excess rainfall, that is, the rain not infiltrated as it falls, which either runs off or remains stored on the surface to be later disposed of by infiltration and evaporation. The excess rainfall so determined is not to be confused with the rainfall over and above a given uniform intensity, which in this paper has been given the name "supra-rain." (3) The amount of water that will be withheld because of surface storage is estimated and deducted from the quantity determined by step (2). This yields the total surface runoff produced by the rain.

This procedure is basically simple, but in application a number of genuinely difficult questions arises. Among these are: (a) What will be the initial infiltration capacity for the degree of wetness existing at the moment the rain begins? (b) How will the infiltration capacity vary during periods when it exceeds the rate of rainfall, both during the initial rain and for periods of low intensity between runoff-producing rain periods? (c) How rapidly will infiltration capacity recover during periods between rains? (d) What is the effect of season? (e) What correction shall be made for surface-storage effects? Each of these troublesome problems calls for a brief discussion.

Effect of antecedent condition--Several methods have been developed for estimating the infiltration capacity that would exist at the outset of any rain, or, in lieu thereof, the location in time of some point on the infiltration curve. The object, of course, is to locate the selected infiltration curve with respect to the rainfall pattern.

The general approach is to seek a relation between initial infiltration capacity and some measure of antecedent condition. The common assumption is that the degree of wetness of the area prior to the storm is the controlling factor, and such measures are usually intended to have a close correlation with soil moisture. Since actual measurements of soil moisture are available only for experimental areas, the problem is commonly two-fold: First, to find a practical measure of wetness; and, second, to discover how to use this measure to predict the initial infiltration capacity or some other point on the standard infiltration-capacity curve.

One measure of antecedent wetness developed by HORNER [1943] for the Black Lands of Texas may be expressed

$$M = F_s + M_a + M_y \quad \ldots\ldots\ldots\ldots \quad (3)$$

where F_s = total infiltration occurring during the rain up to the time infiltration capacity falls to a value of 0.4 in/hr; M_a = a summation of the weighted values of infiltration occurring during the 30 days preceding the rain, the weights used varying from one at zero days prior, to 0.4 at ten days, and to 0.1 at 30 days; and M_y = five per cent of excess over or deficiency below the average precipitation during a 90-day period ending 30 days prior to the rain.

An index of antecedent condition used by the United States Department of Agriculture in several flood-control surveys may be expressed

$$\Sigma(P/T)_n = P_1/1 + P_2/2 + \ldots + P_n/n \quad \ldots\ldots\ldots\ldots \quad (4)$$

where P_n = rainfall recorded on the n^{th} day preceding the rain for which the runoff is being calculated. The value of n usually varies from ten to 20 in practice.

This index is not as closely related to soil moisture as though the depths of infiltration were used instead of values of P. While values of F could be substituted for P in the above equation, it should be pointed out that the use of precipitation has one important advantage in dealing with cultivated lands, namely, that a precipitation index reflects the effect of raindrop pelting, a factor which materially lowers the infiltration capacity of unprotected soils.

Another index of antecedent condition that has been used is the stream flow immediately prior to the rain. The hypothesis behind this is that stream flow in dry periods is related to groundwater level, and this, in turn, is correlated with soil moisture. However, there is no correlation between soil moisture near the soil surface and groundwater level in the summer, for in this season the infiltration from a majority of the rains never reaches the groundwater table. Nor does a dependable correlation generally exist in the dormant season.

At the present time the relation between indices of the type discussed and infiltration capacity must be derived for the particular task in hand by a special study of applicable rainfall and runoff measurements. Ordinarily use is made of records for existing experimental plots and watersheds. Recent studies with artificial rainfall equipment indicate a possibility of establishing correlation between antecedent condition and infiltration capacity by use of this device.

When it is possible to assume wet antecedent conditions, the problem is, of course, considerably simplified.

Variation of infiltration capacity under low intensities--The fundamentals of this problem were covered in the previous discussion of the construction of standard f_p curve. To date, no better solution has been suggested than the application of assumption (b) outlined in that discussion. Its use in constructing actual infiltration curves from standard f_p curves will be evident from a very little study. The use of a mass diagram of the standard f_p curve to estimate the value of f_p at any instant is illustrated in Figure 5.

Recovery of infiltration capacity--For any complex, the rate at which the infiltration capacity recovers between rains must be determined by analysis of records for plots and small watersheds or by the use of artificial rainfall measurements. To date, unfortunately, insufficient data of this sort have been published to obviate the need of a special study for each particular job. It can be confidently expected, however, that the publication of more such information will make possible the development of routine procedures and result in the publication of data in form for convenient application.

Effect of season--Season is not really an independent variable in the infiltration process. Rather it is a sort of catch-all useful only in providing a convenient name for a group of such variables. Important among these are biological activity in the soil, temperature, and soil compaction. The effect of season must be carefully distinguished from that of antecedent soil moisture. It is true, of course, that the soil is ordinarily wetter during certain seasons of the year, and that this will decrease the infiltration capacities in these seasons. But it seems wise to separate the effect of moisture and seasonal effect, even if the other variables are left in a catch-all. Strictly speaking, of course, each of the independent variables which produce the seasonal effect should be separately related to infiltration, and eventually research will undoubtedly be undertaken to accomplish this. The need for a seasonal correction will then disappear.

Until more information on the effect of season has been published, it will be necessary to add a study of season to each individual application of the infiltration theory in which this factor plays a part.

Surface-storage effects--The solution of this problem, like those outlined previously, usually requires an analysis of specific data applicable to the area in hand. In other words, the field is not yet developed to the point where a value may be obtained by routine reference to published data. Nevertheless, there are two considerations that mitigate the anxiety of the practicing hydrologist in approaching this problem: First, for the large storms, and these are the storms in which the practicing hydrologist is ordinarily interested, a fairly large error can be made in estimating storage without introducing any great percentage of error in the calculated runoff; and second, surface storage does not depend upon as many variables as some of the other factors entering into the runoff problem. For a given cover, or a given cultural treatment, surface storage is about the same for all soils and all parts of the world. Once factors are determined for a given cover or treatment, therefore, they can be widely used.

The publication of the results obtained by numerous investigations already concluded will go far toward fulfilling the present need for information on surface storage effects.

The use of indices

It has been shown previously that a multiple-complex index can, strictly speaking, be used only for rains, watersheds, and conditions identical with those for which it was derived. Nevertheless, if a large number of such indices are available for a wide variety of storms and watersheds, and an intelligent selection is made for a given basin, very useful estimates may be obtained. At any rate, such indices are an improvement over coefficients that are simple ratios of runoff to rainfall or of rate of runoff to rainfall intensity. It must be appreciated, however, that the use of such indices does not constitute a rational application of the infiltration theory, and that the results derived by their use must always be considered empirical.

Whenever possible, indices should be derived for, and applied to, individual rain periods, not to storms comprised of several rain periods.

An index can be intelligently used only if the procedure by which it was derived is known, for the application is necessarily a reversal of the derivation.

Application of the ϕ index--The application of the ϕ index is very simple. When estimates are to be made for several complexes, a supra-rain curve is usually prepared (see Fig. 6). This curve is entered with the selected value of ϕ on the rainfall-intensity scale. The value corresponding to this ϕ on the other axis will be the runoff produced by the rain. The same result can obviously be secured without constructing a supra-rain curve by planimetering or otherwise measuring the area of the rainfall-intensity diagram over and above an intensity equal to ϕ.

Application of the f_{av} and W indices--The procedure by which the W index is applied is the reverse of that by which it is calculated. The time interval during which infiltration would take place at capacity rates, T_c, is estimated from an inspection of the intensity-time graph for the rain and a knowledge of the area. By multiplying this value of T_c by the adopted value of f_{av} or W, the quantity F_c is obtained. The volume of initial infiltration F_i is then determined from the rainfall graph, and the surface storage S_e is estimated from a knowledge of the watershed. Given these quantities, the surface runoff Y_s is calculated from the expression

$$Y_s = P - (F_c + F_i + S_e) \qquad (5)$$

Application of the W_{min} index--This index is used only in estimating maximum flood runoff. For a great storm, the quantities F_i and S_e in Equation (5) are usually small in comparison to the runoff and, if so, may be neglected. Under these circumstances, the runoff can be calculated in the same way as for the ϕ index. In a general case, of course, the W_{min} index is used in exactly the same manner as the W index.

The choice of indices--In deriving indices for an area containing but a single complex, there may be some advantage in going to the extra trouble of calculating the f_{av} index rather than the simpler ϕ index. But in dealing with multiple-complex watersheds, the corresponding W index has little, if any advantage over the ϕ index. If a better result is required than that attainable with the latter, it will usually be found advisable to discard the index approach for the calculation of runoff by individual complexes by the use of infiltration curves.

Some representative indices--Values illustrative of the general magnitude and variation of ϕ are given in "References" at the end of the paper.

Summary of principal needs

In the foregoing there has been set out a number of the problems that must be solved before the infiltration approach can become a convenient and dependable tool for general use. These may be summarized in the form of the needs of the technician who undertakes to calculate runoff.

It is hardly necessary to say that the greatest of all these needs is a better understanding of infiltration as a physical process. While a discussion of infiltration, per se, has not been attempted in this paper, it is obvious from the very nature of the problems uncovered that the major deficiency is a lack of knowledge of the physics and chemistry of infiltration. If this deficiency is made good, many problems will simply disappear. But in addition to relief from this poverty of fundamental knowledge, the practicing technician has immediate need, for a wide variety of complexes, of:

(1) At least an empirical knowledge of the variation in infiltration capacity during periods when this capacity exceeds rainfall intensity;

(2) A means of predicting the initial infiltration capacity at the outset of any rain. This requires the development of measures of antecedent condition and the relating of these measures to initial infiltration capacity;

(3) Information on the recovery of infiltration capacity during rainless periods;

(4) A systematic presentation of the characteristics of standard infiltration-capacity curves and, in particular, of the effect of rainfall intensity, season, and similar factors upon the relative shape of such curves;

(5) Experimental information on the effect of season, or on the factors that control seasonal effect, upon infiltration;

(6) More and better data with which to estimate surface-storage effects. To this end artificial rainfall experiments should be made in which surface storage is measured directly;

(7) Better procedures and techniques for the derivation of infiltration data and the routine calculation of surface runoff;

(8) A better understanding of the potentialities and limitations of the artificial rainfall method of securing infiltration data, and standardization of equipment and techniques;

(9) Numerous direct comparisons of calculated runoff with the gaged runoff from large watersheds;

(10) Publication of large quantities of infiltration data covering a wide range of conditions, and eventual systemization of these data in a form for convenient use.

Eventually there must be developed a means of constructing standard infiltration-capacity curves for complexes of known physical characteristics in the absence of specific experimental data. It may be expected that this will result from studies of the relations between these physical attributes and the characteristics (expressed as constants in equations, dimensionless plottings, or otherwise) of experimentally-determined curves.

Recapitulation of some important points

Below is a résumé of points that seem important enough to bear repetition:

(1) The infiltration approach, while a very useful tool, is still in the earlier stages of development, and before it can be generally employed, many problems must be solved and large quantities of data published.

(2) Only surface runoff may be determined by the use of infiltration data. Conversely, infiltration data cannot be derived from measurements of runoff containing subsurface flow.

(3) A rigorous application of the infiltration approach requires that the runoff be separately calculated for each complex and these values summed to obtain the runoff from a multiple-complex area. Obviously, this process cannot be reversed. It follows that infiltration curves for individual complexes cannot be derived from the runoff and rainfall records of a multiple-complex watershed.

(4) The only rational way to calculate the runoff from a single complex is by the use of infiltration curves.

(5) There are three kinds of infiltration curves: (a) Those showing the variation of the actual infiltration rate through a rain or storm period; (b) those showing the variation of infiltration capacity, with time; and (c) standard infiltration-capacity curves.

(6) Infiltration indices, if wisely selected and properly used, yield runoff estimates suitable for many purposes. For a single complex, these indices have a comprehensible physical meaning. For a multiple-complex watershed, the physical significance is obscure. Whether used for single or multiple-complex areas, the results obtained with indices must be considered empirical.

(7) All infiltration data should be accompanied by a full description of the procedure used in their derivation. Only in this way can correct application of the data be insured.

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Washington, D. C.

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DISCUSSION

Victor A. Koelzer (U. S. Bureau of Reclamation, Denver, Colo.)--An excellent treatment of the process of infiltration, as applied to the computation of surface runoff, is given in this paper. A thorough and theoretically correct analysis is given of the various problems entering into the computation of runoff by the infiltration approach.

Since the author stated that one of the objectives of the paper is "to clarify the concepts and principles upon which further progress must be based," it is obvious that the author did not feel that all the refinements he suggests in his analysis are at present fully enough developed or substantiated by basic data to be used by the practicing engineer, that is, the engineer who must make runoff estimates to be used as a basis of design. It is believed rather that the author intended that some of the refinements should apply only to the research engineer, working to improve knowledge of the process of infiltration, and to provide better tools for the practicing engineer to use in solving his problems.

Assuming the foregoing to be the intent of the author, the writer agrees fully with the basic principles outlined in the paper and endorses wholeheartedly his statement of needs for further research, in particular the need for obtaining a greater accumulation of basic data and for providing a wider distribution of those basic data already available. It is believed, however, that discussion of some of the basic principles, pertaining particularly to methods that can be used by the practicing engineer with tools currently available, is in order.

Cook states that since discharge records for ordinary stream-gaging stations are a summation of subsurface and surface flows, the records cannot be used to determine infiltration rates or indices, as the results would indicate the capacity of the watershed to retain water rather than the capacity of the surface to infiltrate water. This is, of course, true. However, in the determination of a maximum probable flood for design purposes, the practicing engineer is interested in total flow that might be expected at a particular point in a stream, which is generally composed of both subsurface and surface flows, and the relative contributions from each source would be, in this problem, of only academic interest. Thus the retention capacity of a watershed, as computed from stream-flow records, rather than the actual infiltration capacity, is the value needed for such design purposes. It is perhaps regrettable that the term infiltration capacity has come into such widespread use in reports on design-flood determination to denote what actually has been the observed retention capacity of a watershed, as determined by studies of stream flow and rainfall records. The writer agrees that it might be better to adopt the term retention capacity to replace the term infiltration capacity to denote this value.

The author further makes the very logical statement that, since runoff is the summation of rainfall less losses for each complex (that is, soil, cover, and surface condition) in the basin, in a large complicated watershed composed of several complexes, surface runoff can be estimated rationally only by summing the separately calculated runoffs from the various complexes. This is demonstrated by a study the writer has made of the runoff from three contributing areas to the Cimmarron River above Englewood Dam site, each area being a different complex and therefore having different retention rates as follows:

Area	Drainage area sq mi	Retention rate in/hr
A	1946	0.20
B	1547	0.25
C	1806	0.40

For the sake of simplicity in the study, it was assumed that the inflow points of the three contributing areas coincided; thus the computed hydrographs of runoff for the three areas could be summed directly to obtain the total hydrograph. Using the design storm determined in the Englewood study, the total hydrograph was determined in two ways; by applying different retention rates for each area, and by applying an average retention rate, weighted according to drainage areas. The results, shown on Figure 1, indicate that discrepancies of 10.9 per cent in peak discharge, and of 8.5 per cent in total flood volume, would result on such a stream if average values of retention rate were used instead of different values for each area. This demonstrates that some error will result if an average retention rate is applied to a watershed composed of several complexes widely varying in nature.

For watersheds in which direct summations can be made of computed hydrographs for individual complexes, it is therefore desirable to compute separate hydrographs for varying complexes in the watershed, as suggested by the author. However, other cases may arise where such a method might necessitate using summation procedures which in themselves are capable of introducing errors as large or larger than that caused by using an average retention rate. Such a case could occur when the inflow points of complexes making up the drainage area are at various points throughout the reach of the main stream, and thus a direct summation of computed hydrographs cannot be made. In such a case the hydrograph for each complex must be routed from its point of inflow to the point of determination of the total hydrograph. This routing procedure, unless based on very accurate channel cross-sections, values of roughness, and slopes, can easily introduce more error than that caused by using an average retention rate. The routing procedure is not necessary if an average retention rate is used, assuming, of course, that the runoff characteristics of the total watershed are such that the flow can be determined by a unit hydrograph for the entire area.

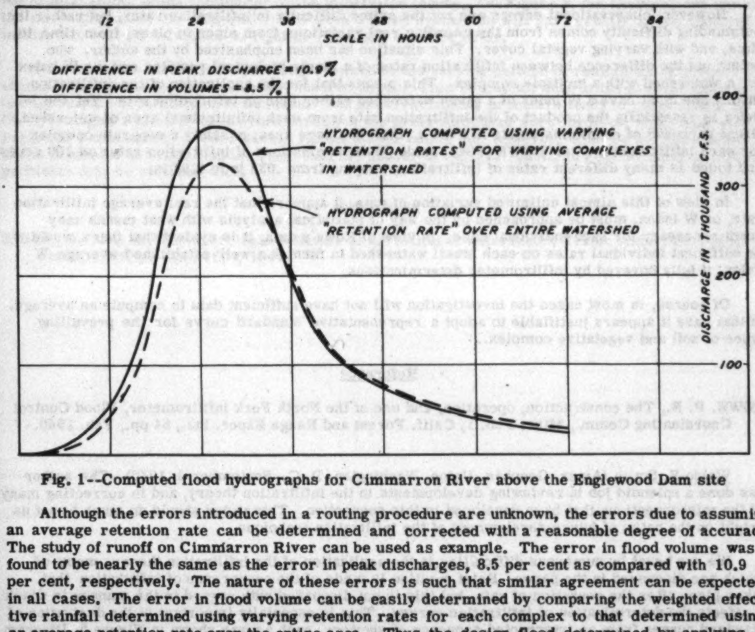

Fig. 1--Computed flood hydrographs for Cimmarron River above the Englewood Dam site

Although the errors introduced in a routing procedure are unknown, the errors due to assuming an average retention rate can be determined and corrected with a reasonable degree of accuracy. The study of runoff on Cimmarron River can be used as example. The error in flood volume was found to be nearly the same as the error in peak discharges, 8.5 per cent as compared with 10.9 per cent, respectively. The nature of these errors is such that similar agreement can be expected in all cases. The error in flood volume can be easily determined by comparing the weighted effective rainfall determined using varying retention rates for each complex to that determined using an average retention rate over the entire area. Thus the design flood determined by applying average retention rates could be corrected with reasonable accuracy by increasing all ordinates of the hydrograph by 8.5 per cent, the amount of error determined in the flood volume. The writer believes that in such cases the resulting error would be considerably less than would be introduced if hydrographs were computed for each complex having a different retention rate, and routed to the point of determination of the total hydrograph.

The writer disagrees with the author when he states that surface storage for any given cover, or a given cultural treatment, is about the same for all soils and all parts of the world. It is believed that land slope would also greatly effect surface storage. In addition, small natural basins without exterior drainage, a characteristic of certain localities, greatly influence surface storage.

Edgar E. Foster (U. S. Bureau of Reclamation, Denver, Colo.)--This paper is an excellent summary of the present usage of the estimation of infiltration rates. It reveals many of the inherent difficulties of using the infiltration theory but indicates means of meeting them.

As the author has indicated, it is not possible to measure rates of infiltration directly on undisturbed soil. The lysimeter could probably be considered an instrument of direct measurement, but the soil would necessarily be disturbed when placed in the lysimeter and would give probably entirely different results from what would be obtained, say, with an infiltrometer on the natural undisturbed site.

With an infiltrometer, measurement of rainfall and runoff are the primary data from which rates of infiltration are computed. Errors of observation of rainfall and runoff are unavoidably carried over into the rate of infiltration. These observational errors are probably small for any one determination of infiltration at one point.

However, observational errors are not the prime difficulty in infiltration rates, but rather the outstanding difficulty comes from the unending real variations from place to place, from time to time, and with varying vegetal cover. This situation has been emphasized by the author, who points out the difference between infiltration rates of a single biological complex and the W index for a watershed with a multiple complex. This means that for the application of the infiltration theory one must have a W index of a given watershed rather than an infiltration rate. Yet the W index is essentially the product of the infiltration rate from each infinitesimal area of watershed. Great variation of conditions exists in even a small drainage area; possibly a separate complex for each infiltrometer site. ROWE [1940] made 50 determinations of infiltration rates on 100 acres and found as many different rates of infiltration, ranging from .038 in to 3.96 in.

In view of this almost unlimited variation of rate, it appears that the real average infiltration rate, or W index, must be approached by the way of statistical analysis with what means may seem necessary for each individual case. In view of Rowe's data, it is evident that there would be sufficient individual rates on each small watershed to furnish a well-established average W index, if fully covered by infiltrometer determinations.

Of course, in most cases the investigation will not have sufficient data to compute an average. In that case it appears justifiable to adopt a representative standard curve for the prevailing types of soil and vegetative complex.

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ROWE, P. B., The construction, operation, and use of the North Fork infiltrometer, Flood Control Coordinating Comm., Misc. Pub. 1, Calif. Forest and Range Exper. Sta., 64 pp., Feb. 1940.

Waldo E. Smith (Amer. Geophys. Union, Washington, D. C., September 9, 1946)--The author has done a splendid job in reviewing developments in the infiltration theory, and in correcting many of the misconceptions that have developed in this connection. This paper should do much to set us aright on the paths of future development of the infiltration technique.

We are beset by numerous difficulties in the application of the infiltration theory, many of which are discussed in the paper. Brief mention is made of the occurrence of infiltration that takes place after the cessation of rain, but this is not discussed with regard to the manner in which it affects the determination of infiltration curves. This is especially important in the derivation of standard curves from an interrupted sequence of showers, such as was shown in Figure 5, Diagram E. At the instant that the rain ceases or the intensity falls below the potential infiltration rate, the entire watershed is covered with a film of water. Through infiltration and lateral surface movement, this film rapidly shrinks so that after a few minutes the numerous slight ridges are no longer covered by water. The recession of the film continues rapidly until infiltration occurs only on the areas occupied by tiny rills and depression storage.

The determination of the recession of the film is a highly complex matter, but an approximation of an equivalent period of duration of infiltration during which it may be assumed that infiltration takes place on the entire area at the potential rate, and after which it is assumed to cease, is not so difficult. In a study by the writer [See "References" at end of discussion, SMITH, 1944] a five-minute equivalent period was determined by trial on small, fairly steep watersheds on which depression storage was quite small. This period was found to be the one giving the least erratic distribution of points in the computation of the standard infiltration curves derived. This would seem to the writer to be a reasonable criterion for such equivalent period.

The author in his treatment has accepted the common assumption that the soil mantle is an inert mass that is itself not affected by the rainfall. For granular soils the error is perhaps not serious, but in the case of colloidal soils the effect is considerable. The writer has seen data for tests on such soils in which the terminal infiltration rate at the end of a "dry run" has been several times greater than the initial infiltration rate at the beginning of a "wet run" 24 hours later. Water entered the colloids, causing them to swell and to seal the surface almost completely against further infiltration. Some account must be taken of such phenomena in any general application of the infiltration theory.

The author discusses the various methods that have been evolved for the placing of standard infiltration curves in proper time sequence on hyetograms or intensity-time graphs of rainfall. To the writer's knowledge none of these has yet been shown to be very reliable. Yet this is one of the crucial points in the application of the infiltration theory. On Figure 8, for example, any one of the three diagrams, the computed runoff from a given hyetogram will vary greatly as the standard infiltration curve F is shifted to right or left along the time scale.

No mention is made of the difficulty involved in the varying pattern of rainfall for a given storm over a watershed of even a few hundred acres. This is a factor that involves much time in the application of infiltration techniques. The great variability in pattern tends to raise doubts in the hydrologist's mind as to the justification of the great amount of work involved, especially with regard to the accuracy of the results. As the author points out, however, when we are interested in the problems of major floods rather than the matter of surface runoff, in general many of these problems may be circumvented.

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REVIEWS AND ABSTRACTS

KIMURA, HISASHI (ed.), Results of the International Latitude Service, 1922.7-1935.0, v. 8, 237 pp., 1940.

The eighth volume of the Results of the International Latitude Service, covering the period from 1922.7 to 1935.0 was published at Mizusawa, Japan, in 1940, under the auspices of the International Astronomical Union. This was about three years before the death of Hisashi Kimura, former Director of the International Latitude Service, under whose direction this volume was prepared. Because of the War all of the entire edition was held in Japan but is now on its way to this country. When the shipment is received by the United States Coast and Geodetic Survey, copies will be sent to those interested.

In general this volume is similar to preceding volumes of the series. The x and y coordinates of the variable pole are referred to a mean position of the pole and are given at intervals during the period covered by the discussion. There is a systematic difference between the latitudes obtained from observations made during the evening and those made in the latter part of the night, and the results for each class are given separately. The mean pole to which the variable pole is referred is the same as that used in Volume VII of the series and differs from the mean pole for the years 1900-1912, the first 12 years of the International Latitude Service, by 0''.048 in the x coordinate and 0''.072 in the y coordinate. This might suggest a slow shifting of the mean North Pole in the general direction of eastern North America, but Kimura does not accept this conclusion. By a different treatment of the figures he concludes that the stations Caloforte, Gaithersburg, and Ukiah showed no significant changes in mean latitude during the 35 years since 1900, but that during that time the station Mizusawa, for some reason, moved relatively to the others about 12 feet toward the south.

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the Transactions:

Vol. 27, no. 3, June 1946, p. 426, 3rd line of the paragraph closing the page; this should read "showing graphically . . ." instead of "showing geographically . . ."

Vol. 27, no. 3, June 1946, p. 456 concerning the late Robert A. Bartlett. We are advised by Sherman A. Wengerd that Captain Bartlett's last voyage to the Far North was not in 1935, and that he took the schooner Morrisey into Arctic or Sub-Arctic regions every summer since 1935, and was completely prepared to go again in 1946. His active work on Arctic exploration thus continued, literally, to the last minute.

International Union of Geodesy and Geophysics--An Extraordinary General Assembly of the International Union of Geodesy and Geophysics was held at Cambridge, England, July 29 to August 2, 1946. Sixteen countries were represented. The principal business before the meeting was the preparation of new statutes and by-laws. Under the new statutes Professor Helland-Hansen, elected at Oxford, vice Dr. D. la Cour, deceased, was confirmed as President. Brigadier Winterbotham of England and Dr. N. E. Nörlund of Denmark were elected Vice Presidents, and Dr. J. M. Stagg of England was confirmed as General Secretary. The next meeting of the Union will be held in Norway in 1948. Walter D. Lambert was the representative from the National Research Council.

General Assembly of International Council of Scientific Unions--The first Postwar General Assembly of the International Council of Scientific Unions was held in London, England, July 22 to

24, 1946. Walter D. Lambert of the United States Coast and Geodetic Survey attended as the representative of the National Research Council of the United States. Representatives of 21 nations were in attendance. On the agenda were a discussion of the future developments of the Council's activities, and the policy to be pursued, the draft agreement with the United Nations Educational, Scientific, and Cultural Organization, and reports from the member Unions which indicated a rapid revival of activity in the postwar period. Jno. A. Fleming, General Secretary of the American Geophysical Union, was elected President. Others elected to the Executive Committee are B. Němec (Prague), Émile Borel (Paris), Vice Presidents; F. J. M. Stratton (Cambridge), General Secretary; J. N. Mukherjee (New Delhi), and H. Solberg (Oslo), members. H. R. Kruyt is retiring President. The next General Assembly is to be held in Copenhagen in 1949, with annual meetings of the Executive Committee in the interim. A full account of the General Assembly was published in Nature, v. 158, no. 4007, pp. 227-229, 1946.

The International Association of Geodesy, I. U. G. G.--A meeting of the Permanent Commission of the International Association of Geodesy was held at Paris, France, August 5-7, 1946. Seventeen countries were represented, and many important matters were acted upon. The following officers were elected to serve until the end of the 1948 General Assembly of the Association: President, Walter D. Lambert, United States of America; Vice Presidents, C. F. Baeschlin, Switzerland, and H. S. Jelstrup, Norway; Secretary, Pierre Tardi, France; and Associate Secretary, G. R. Laclavère, France. Chairmen of Sections and ex-officio members of the Executive Committee were elected as follows: Triangulation, Pierre Jacquinet, France; Leveling, Jean Vignal, France; Geodetic Astronomy, N. E. Nörlund, Denmark; Gravimetry; F. A. Vening Meinesz, Netherlands; and Geoid, J. de Graaff Hunter, Great Britain.

UNESCO Month--In July 1946, Congress passed a Joint Resolution authorizing the President to accept membership for the United States in the United Nations Educational, Scientific, and Cultural Organization. In accepting such membership, President Truman stated that he attached "the greatest importance to this agency. UNESCO will summon to service in the cause of peace the forces of education, science, learning, and the creative arts, and the agencies of the film, the radio, and the printed word through which knowledge and ideas are diffused among mankind. The Government of the United States will work with and through UNESCO to the end that the minds of all people may be freed from ignorance, prejudice, suspicion, and fear, and that men may be educated for justice, liberty, and peace. If peace is to endure, education must establish the moral unity of mankind."

The Department of State has set aside the period from October 28 to November 30 as UNESCO Month, and invites all national organizations to participate in its observance. The Office of the Union desires to cooperate and assist any local or regional group of members in any plans it may undertake in this connection.

Pan American Meeting in Caracas--The Fourth General Assembly of the Pan American Institute of Geography and History and the Third Consultation on Cartography were held at Caracas, Venezuela, from August 22 to September 1, 1946. Representatives totalling about 150 persons from nearly all of the American republics and Canada, including various educational and scientific organizations, were in attendance at the various sessions. The Division of Studies and Investigations of the United Nations was represented by Dr. Jean Gottman; the International Union of Geodesy and Geophysics was represented by Dr. F. A. Vening Meinesz, University of Utrecht, Amersfort, Holland, and Captain C. L. Garner, United States Coast and Geodetic Survey. One of the United States delegates also represented the American Geophysical Union.

The four sessions of the Institute considered various important current problems on geography and history. The Commission on Cartography dealt with current problems in surveying and mapping under the following heads: Geodesy, topography, hydrography, aeronautical charts, special surveys and maps, and urban surveys. The fifth assembly of the Institute is to be held in Santiago, Chile, in 1949, and the fourth consultation on cartography is scheduled for Buenos Aires in the latter part of 1947.

Meeting of the Commission on Continental and Oceanic Structure--The Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics met in Ottawa, Canada, September 4-6, 1946, to consider plans for the preparation of its report for the Eighth General Assembly of the IUGG, scheduled for 1948. Representatives from the United States, Canada, England, the Netherlands, and Finland were in attendance. The Chairman of the Commission is R. M. Field.

Meeting of the Committee on the Social Value of the Earth Sciences--The Committee on the Social Value of the Earth Sciences, established at the Oxford (England) meeting of the Executive Committee of the IUGG in December 1945, held its first meeting in South Duxbury and Needham, Massachusetts, September 9-11, 1946. The members considered the purposes of the Committee as outlined by the IUGG (see Trans., v. 27, no. 2, pp. 209-214, 1946) and decided to prepare a brochure bearing on these purposes. R. M. Field is Chairman of the Committee.

Geophysical Institute established at the University of Alaska--An act authorizing the establishment of a Geophysical Institute at the University of Alaska was passed by the 79th Congress and signed by the President. The way is thus cleared for the appropriation of funds in time for actual construction to proceed in the summer of 1947.

Earthquakes in June, July, and August, 1946--The Institute of Geology of the National University of Mexico reports that the deep-focus earthquake of June 7, 04^h13^m U. T. (listed in the Transactions, v. 27, no. 4, 1946) was felt in the southeastern states of Mexico. The shock was especially noticeable on the Isthmus of Tehuantepec. Some damage was reported at Ixtepec, Oaxaca. A special study of the seismograms of the earthquake of June 23, 17^h13^m (reported in the Transactions, v. 27, no. 4, 1946) is being made by the Dominion Observatory, Ottawa, Canada. Original records or photographic copies are being received for this purpose by R. Meldrum Stewart, Dominion Astronomer. B. Gutenberg reports that an earthquake felt at Chico, California, on July 7, was recorded by Pasadena at $06^h56^m57^s$ U. T. On July 11 (Tables 1 and 2), another shock, very similar to the one of June 7, was felt in the states of Veracruz, Oaxaca, and Chiapas, Mexico. The National University of Mexico reports that the intensity was about IV on the Mercalli scale. A severe earthquake was felt throughout northern Chile on August 2 (Tables 1 and 2). Extensive damage was reported from Vallenar and Copiapo. Two persons were reported killed in the latter city. The series of West Indian earthquakes, which began with the violent earthquake of August 4, was still continuing on August 21, 1946. Minor shocks and a major shock of this series were recorded by seismograph stations on this date.

In addition to the physical damage caused by some of the quakes of this series, the continuation of the series for such a long interval of time tended to create panic among the people. About 75 (estimate) of the series have been strong enough to be recorded by seismographs 3000 miles from the epicenter. Moreover, there were many small local shocks; San Juan, Puerto Rico, reported a total of 158 tremors recorded in the period August 4 to August 8 alone. The seismograms of the individual earthquakes show certain similarities, but they are not exact replicas of each other. In the first place there are the variations in intensity already mentioned, then too the seismograms suggest that the earthquakes may have originated from various places in an epicentral region. Moreover, they may not have had the same focal depths; this is suggested especially by the quake of August 21, which may have had a depth of focus of 50 km, but this will require more than a preliminary examination for positive statement.

The most violent of the series to date was the earthquake of August 4. Gutenberg rated the magnitude of this shock as 8 to 8-1/4 from the Pasadena records. The determinations of the USCGS and JSA (Tables 1 and 2) place the epicenter in the western part of the Puerto Rican Trough just off the Peninsula and Bay of Samana on the northeast coast of Hispaniola Island. The deepest known sounding in the North Atlantic Ocean was made in the Puerto Rican Trough by the U. S. S. Milwaukee, which reported a value of 8750 m.

A preliminary check of casualties in this series showed a total of 73. However, communications were so badly disrupted that it will require some time for a thorough and accurate report. Although the quakes were felt on other islands of the West Indies, such as Cuba and Puerto Rico, Hispaniola Island, occupied on the west by Haiti and on the east by the Dominican Republic, was the most severely affected. Early reports indicate that at least 11 towns in the Dominican Republic were badly damaged. Santiago, the largest city in the region, had considerable building destruction. The earthquake of August 4 was followed by a sea wave which struck the north coast of the Island and swept in Escosesa Bay causing severe havoc in coastal towns, especially Matanzas and Villa Julia Molina. Ciudad Trujillo, the capital city of the Dominican Republic, situated on the south coast, reported some building damage but no sea wave.

Table 1--United States Coast and Geodetic Survey epicenters

Date	Time U. T.	Epicenter		Remarks
		Lat.	Long.	
	h m s	°	°	
June 23	17 13 20	49.9 N,	125.3 W	Georgia Strait
June 24	15 48 00	14.0 N,	91.0 W	Coast of Guatemala
June 26	07 53 36	14.0 N,	91.0 W	Coast of Guatemala
July 1	02 52 24	64.0 N,	148.0 W	Near Fairbanks, Alaska
July 11	04 46 36	17.0 N,	94.0 W	Isthmus of Tehuantepec, slight depth
July 18	06 07 06	50.0 N,	129.0 W	Slightly less than 100 km depth
July 18	07 16 30	Aftershock of previous earthquake		
July 25	16 42 06	51.0 N,	179.0 W	Aleutian Islands
July 26	06 44 42	21.6 S,	70.0 W	Northern Chile
Aug. 2	19 18 42	27.0 S,	70.0 W	Near Copiapo, northern Chile, slight depth
Aug. 4	17 51 07	19.3 N,	69.0 W	Nine miles east of Samana Peninsula, Dominican Republic
Aug. 8	13 28 24	Aftershock of previous earthquake		
Aug. 11	01 54 18	8.0 S,	155.0 E	Solomon Islands
Aug. 15	15 23 54	22.0 S,	170.0 E	Loyalty Islands
Aug. 21	19 17 36	Aftershock of August 4 quake off Samana Peninsula		

The earthquake of August 8 ranked second in severity. Gutenberg rated the magnitude as 7-1/4 to 7-3/4 from the Pasadena records. This shock also set up a sea wave. Airplane observers who made trips after August 8 report that the north coast of Hispaniola Island showed effects of the earthquakes. Sea-cliff slumping and some changes in drainage were evidenced.

The United States Coast and Geodetic Survey is making a special study of the seismograms of these earthquakes, especially the records of August 4 and August 8.

The epicenters given in Tables 1 and 2 were reported by the United States Coast and Geodetic Survey and the Jesuit Seismological Association cooperating with Science Service and a selected group of widely scattered seismological stations.

Table 2--Jesuit Seismological Association epicenters

Date	Time U. T.	Epicenter		Depth
		Lat.	Long.	
	h m s	°	°	km
June 23	17 13 19	50.0 N,	125.0 W	
June 24	15 48 16	14.9 N,	89.7 W	200
June 26	07 53 50	14.3 N,	91.3 W	200
July 1	02 52 24	64.0 N,	149.0 W	
July 11	04 46 30	16.7 N,	94.6 W	50-100
July 18	06 07 02	50.0 N,	130.0 W	50
July 18	07 16 30	Aftershock of six hr		
July 18	07 20 10	Aftershock of six hr		
July 25	16 42 24	50.6 N,	177.3 W	50
July 26	06 44 53	19.8 S,	70.9 W	80
Aug. 2	19 19 01	25.5 S,	71.1 W	80
Aug. 4	17 51 07	19.2 N,	68.9 W	
Aug. 8	13 28 27	Aftershock of August 4		
Aug. 11	01 54 26	8.4 S,	155.9 E	
Aug. 21	19 17 43	19.2 N,	68.9 W	50

Earthquakes in 1946 not previously reported in the Transactions--The National University of Mexico states that the earthquake of January 11, 18^h00^m U. T. (Table 3), was reported felt in Puerto Mexico (Coatzacoalcos), Mexico. The JSA epicenter is east of Puerto Mexico in the state of Tabasco. Strasbourg reports that the earthquake of March 12, 02^h00^m U. T. (Table 3), was destructive in the region about Shiraz, Persia. On March 29 two earthquakes occurred in northwestern South America between 07^h00^m and 08^h00^m U. T. The first shock was tentatively located by the JSA at 2°.8 N, 75°.8 W; origin time $07^h17^m35^s$. I. E. Ramirez of Bogota reports that this earthquake was felt strongly at Popayan, Coconucos, and Purace, Colombia. The second shock, reported felt at Guayaquil, Ecuador, was tentatively located by the JSA at 2°.0 S, 80.° W; origin time $07^h26^m12^s$. A series of tremors was reported felt in the Rabaul area of New Britain on May 3. Ground slumping was discovered after the tremors, which were described as severe. The mean epicenter (based on USCGS and JSA determinations) of the main earthquake was 8°S, 154°E; origin time $22^h23^m37^s$. The two large Turkish provinces of Mus and Ezurum, west and northwest of Lake Van, were rocked by a destructive earthquake on May 31. In delayed dispatches the Red Cross reported that the death toll was well over 1300. The communities of Karliova, Varto, and Ustukan were particularly damaged. The epicentral region was given by the JSA as 38°N, 41°E; origin time $03^h12^m40^s$ U. T.

The tentative epicenters in Table 3 were reported in the supplementary bulletins of January, February, and March, 1946, of the Jesuit Seismological Association cooperating with Science Service, the United States Coast and Geodetic Survey, and a selected group of widely scattered seismological stations.

Table 3--Tentative epicenters for earthquakes of 1946

Date	Time U. T.	Epicenter		Depth
		Lat.	Long.	
	h m s	°	°	km
Jan. 4	19 43 47	10.0 N,	84.0 W	50
Jan. 11	01 33 30	43.5 N,	130.0 E	600
Jan. 11	18 41 33	18.0 N,	93.5 W	
Feb. 4	03 44 58	52.2 N,	175.5 W	150
Feb. 12	02 43 30	36.0 N,	5.0 E	
Mar. 12	00 02 00	35.8 S,	105.5 W	
Mar. 12	02 21 50	32.0 N,	53.0 E	
Mar. 25	22 16 47	15.5 N,	93.2 W	
Mar. 25	08 47 41	19.0 N,	74.7 W	

Pacific Science Conference--A conference relating to a science survey of the Pacific was held in Washington in June 1946, under the auspices of the National Research Council. A number of recommendations was made to the National Research Council, among them being the establishment of a permanent organization, to be called the Pacific Science Survey, with the establishment of a number of divisions, including Earth sciences. Oceanography, meteorology, hydrology, gravity determinations, geomagnetism, and mapping were especially mentioned.

Fellowships for Arctic research--The Arctic Institute of North America has announced the availability of two fellowships for research in the Arctic or Sub-Arctic during 1947. Interested persons should apply to the headquarters of the Institute in Montreal for further information.

Third Hydraulics Conference at the University of Iowa--The Iowa Institute of Hydraulic Research sponsored its third conference on hydraulics on June 10-12, 1946. A series of 16 papers was presented to emphasize the application of wartime developments to the peacetime practice of hydraulics. The operation of the hydraulics laboratory of the Institute was also a feature of the three-day conference. About 300 persons attended, coming from all parts of the United States and from Canada. As in past conferences (First, 1939; Second, 1942), the papers will be published by the Institute.

Research Associates wanted for hydraulic research--The Iowa Institute of Hydraulic Research at the University of Iowa has sent out a call for recent graduates desiring to secure advance degrees in hydraulics as Research Associates. Other appointments in research work are also open.

New seismographs at Regis College--Two horizontal component Macelwane-Sprengnether seismographs were installed at Regis College, Denver, Colorado, during August. The new installations were made in the basement of the Administration Building, where a Wiechert instrument has been in operation since 1909. A new reinforced-concrete pier, which rests on the Denver Formation, was constructed in 1945. A. W. Forstall and J. V. Downey, in charge of the Denver station, expect to have the new instruments in routine operation in September.

American Congress on Surveying and Mapping--The American Congress on Surveying and Mapping held its Sixth Annual Meeting at Washington, D. C. on June 28-29, 1946. Technical papers were presented on electronic developments in surveying and mapping; on surveys for property boundaries, urban areas, and highway planning and construction; on developments in surveying instruments and in cartographic and reproduction methods; on coordination and administration of surveying and mapping activities; and on other related subjects.

Course on the Ionosphere--Stanford University is now offering a one-term course on the Ionosphere. This was given for the first time during the summer term of 1946.

Russian work in geophysical prospecting--A new thermal method of prospecting for minerals has been developed by S. S. Kovner that has been applied successfully on an experimental scale in Bashkivia. A seismic oil-prospecting expedition has been at work on the Apsheron Peninsula in the Baku area with the aim of giving practical help to oil-prospecting organizations and carrying out experiments on peculiarities of the propagation of seismic waves in non-homogeneous media. The work is under the direction of G. A. Gamburtsev.

Work of the Hydrophysical Laboratory of the U. S. S. R.--The relation between oceans and continents, and storms have been two major problems studied. Specific problems have dealt with the propagation of sound waves at sea and the development of a new type of acoustic analyses, the problems of ice formation, and the corrosion of reinforced concrete structures under sea conditions.

PERSONALIA

Tom F. W. Barth of the Mineralogical Institute of Oslo will spend the winter of 1946-47 at the University of Chicago as Visiting Professor of Geochemistry.

Kenneth G. Brill has accepted an Assistant Professorship in Geology at the Institute of Geophysical Technology of St. Louis University. He was head of the Department of Geology of the University of Chattanooga until he assumed his new post in September, 1946.

J. E. Christiansen-has been appointed Dean of the School of Engineering, Industries, and Trades at Utah State College. He succeeds G. D. Clyde.

G. D. Clyde, formerly Dean of the School of Engineering, Industries, and Trades at Utah State College, is now Chief of the Division of Irrigation of the Soil Conservation Service, with headquarters at Logan. He succeeds W. W. McLaughlin.

Richard M. Foose has accepted a position as Professor of Geology at Franklin and Marshall College. He was previously with the Pennsylvania Geological Survey at Harrisburg.

Robert W. Gay, who until recently was with the Tennessee Valley Authority with headquarters at Chattanooga, Tennessee, has taken up duties with the United States Bureau of Reclamation with headquarters at Boise, Idaho.

W. Heiskanen of the Isostatic Institute of the Association of Geodesy, International Union of Geodesy and Geophysics, located in Helsinki, arrived in the United States in May 1946 for the purpose of renewing scientific relationships. He attended the meeting of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics held in Ottawa, September 4 to 6, 1946, and returned to Finland later in the month.

Varnakale L. Jones, formerly with the Stanolind Oil and Gas Co. and more recently on consulting work in geophysics, has been appointed Assistant Professor of Geophysics at the University of Tulsa. He will continue his practice as consulting geophysicist.

A. A. Kalinske, until recently associated with the St. Anthony Falls Hydraulics Laboratory of the University of Minnesota, is now Chief Hydraulic Engineer of Infilco, Incorporated, with headquarters in Chicago, Illinois.

W. W. McLaughlin, Chief of the Division of Irrigation of the Soil Conservation Service, has retired after many years with that Division. He had been chief of the Division since 1931.

John H. Melvin has been appointed District Geologist, United States Engineer Office, Omaha, Nebraska, where he will be engaged in the geological engineering phases of the Missouri River Development Program.

E. F. Osborn has left the Eastman Kodak Co. in Rochester to become Chairman of the Department of Earth Sciences and Professor of Geochemistry at the Pennsylvania State College.

Thomas G. Thompson, Director of the Oceanographic Laboratories of the University of Washington, has been elected President of the Pacific Division of the American Association for the Advancement of Science, at its first Postwar meeting, held at the University of Nevada in June.

F. A. Vening Meinesz returned to the Western Hemisphere from The Netherlands in August. He attended the Fourth General Assembly of the Pan American Institute of Geography and History and the Third Pan American Consultation on Cartography in Caracas, August 22 to September 2, 1946, and the meeting of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics held in Ottawa September 4 to 6. His mission, a continuation of one started during the winter of 1945-46, is, among other things, for the reestablishment of scientific connections in the Postwar period, and for the arrangement of exchange of students and faculty members between Dutch and American universities. He left the United States for the Netherlands in the latter part of September, 1946.

Lawrence A. Warner, formerly with the United States Geological Survey, has recently become a member of the teaching staff of the Department of Geology, University of Colorado.

Harry C. Dukes, veteran water master on the Truckee River in Nevada and member of the South Pacific Regional Committee of the Section of Hydrology, died June 22, 1946, at Reno, Nevada, at the age of 68. He was born at Newman, Iowa, and at the age of 14 removed with his parents to California, where he received his higher education in medicine, but he became interested in water problems of the Southwest, to which his professional career was devoted.

Joseph Geszti, whose contributions in geophysics and geology have been great, was killed by the Nazis during the closing days of the siege of Budapest.

John C. Hoyt, hydraulic engineer for the Water Resources Branch of the United States Geological Survey for many years, died at Paris, Virginia, on June 21, 1946, after several years of declining health. He was 72 years old. He was born in Lafayette, New York, and completed his formal education at Cornell University in 1897.

Stanislas Kalinowski, organizer and Director of the Swider Geophysical Observatory in Poland, died in Swider on March 27, 1946. Professor Kalinowski did much to increase the knowledge of the distribution of the geomagnetic elements in Poland both through survey and observatory work. He was a familiar figure at international scientific meetings where he ably represented the interests of his country.

Eliot G. Mears, Professor of Geography and International Trade at Stanford University, died at Middlebury, Vermont, on May 27, 1946, at the age of 57. He was on a tour while on leave from Stanford.

L. Steiner, world-renowned Hungarian geophysicist and, since 1932, Director of the Hungarian Meteorological Institute, died by committing suicide at the time of the German occupation of Hungary in the spring of 1944. His successor as Director is A. Réthly.

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UNION, SECTION, AND COMMITTEE ACTIVITIES

Report of Committee on Audit for Fiscal Year, July 1, 1945, to June 30, 1946

A. G. McNish (Chairman), R. H. Weightman

Your Committee on Audit has examined the books of the Union for the fiscal year ending June 30, 1946, and found them in agreement with the financial statement as prepared by the General Secretary's Office and shown below. The balance on hand as of June 30, 1946, was $13,447.41, which is substantiated by a bank balance of $14,461.06, from which must be deducted $1,013.65 for checks outstanding. Expenditures are all carefully posted and supported by vouchers, and individual payments of dues are indicated by individual entries on bank deposit slips and on individual file cards for each member.

Your Committee wishes to commend the efficiency and clarity of the bookkeeping system practiced by the Executive Secretary and his assistants. The books are in better shape this year than ever before within the several years' experience of your present Committee.

Financial Statement, Fiscal Year, July 1, 1945, to June 30, 1946

Receipts		
Cash balance, July 1, 1945, as reported from June 30, 1945		$ 8,864.89
American Geophysical Union	$ 8,705.79	
William Bowie Medal Fund	159.10	
Dues, 1942-1947		13,263.30
1942	$ 9.00	
1943	13.00	
1944	75.00	
1945	1,319.00	
1946	11,469.30	
1947 et seq.	78.00	
Life	300.00	
Sales of Publications		4,951.42
Transactions	$ 2,706.31	
Reprints	2,235.89	
Bibliography of Hydrology	2.55	
Exhibit Maps	6.67	
Miscellaneous Contributions		49.48
Grants		7,400.00
Rockefeller Foundation	$ 7,000.00	
National Research Council	400.00	
Total receipts ($8,864.89 + $25,664.20)		$34,529.09
Disbursements		
Transactions (3 numbers) of 1945 and (3 numbers) of 1946		$ 6,563.92
Reprints		1,581.23
Expenses, General Secretary's Office		10,751.18
Services	$ 9,041.34	
Equipment	3.70	
Stationery and Miscellaneous	863.57	
Postage and Express	842.57	
Committees		1,699.03
Executive	$ 88.10	
Membership	294.93	
Editorial and Publication	1,316.00	
Sections		102.10
Seismology	66.26	
Hydrology	31.31	
Geodesy	4.53	
27th Annual Meeting (1946)		378.22
William Bowie Medal		6.00
Total disbursements		$21,081.68
Balance, June 30, 1946		$13,447.41

Riggs National Bank per statement of June 30, 1946	$14,461.06
Less checks outstanding:	

No.		No.	
1874	$ 1.80	1895	$ 75.00
1885	83.00	1896	75.00
1886	73.13	1897	75.00
1888	15.00	1898	75.00
1890	75.00	1899	75.00
1891	1.50	1900	67.44
1892	37.50	1901	10.00
1893	75.00	1903	7.50
1894	75.00	1904	7.78
		1906	109.00

Total checks outstanding	1,013.65
Balance June 30, 1946, as above	$13,447.41

Distribution of balance

American Geophysical Union	$13,294.31	
William Bowie Medal Fund	153.10	
		$13,447.41

Bills receivable		
Publications		$ 565.58
Transactions	$ 399.35	
Reprints	166.23	
Dues		2,260.00
Fifty Members, 1945 and 1946	$ 400.00	
Three hundred seventy five Members, 1946[a]	1,860.00	
Total bills receivable		$ 2,825.58
Bills payable		
Kirby Lithographic Company	$ 811.53	
Evening Star Newspaper Co.	10.08	
Telegraph and telephone	17.99	
Section of Geodesy	4.45	
Reprints in advance	101.80	
Dues of 1947 et seq. paid in advance	78.00	
Total bills payable		$ 1,023.85

Recapitulation

	A. G. U.	Bowie Medal Fund	Total
Cash balances	$13,294.31	$153.10	$13,447.41
Bills receivable	2,825.58	0.00	2,825.58
Totals	$16,119.89	$153.10	$16,272.99
Bills payable	1,023.85	0.00	1,023.85
Net balances	$15,096.04	$153.10	$15,249.14

Cost of equipment owned by American Geophysical Union

One 18-inch large primer Burroughs typewriter, serial No. 60A232450	$190.80
One 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
Two 4-drawer, 5 × 8-inch steel filing cases (gift)	0.00
Two steel posture chairs	22.00
One Globe-Wernicke, 2-pedestal, flat-top steel desk, A. G. U. No. 1, 60 × 34 inches	49.18
One Triner postal scale, 4 lbs. by 1/2 oz.	16.20
One Arrow stapler	6.75
One walnut flat-top desk, A. G. U. No. 2, 34 × 66 inches, with glass top	95.43
One walnut typewriter desk, A. G. U. No. 3, 34 × 60 inches, with glass top	100.72
One walnut typewriter desk, A. G. U. No. 4, 34 × 60 inches, with glass top	89.72
One walnut chair	21.50
One costumer, walnut finish	3.50

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[a] Of these, five owe but $2.00 each on dues of 1946.

Cost of equipment owned by American Geophysical Union (continued)

Ten desk trays, walnut finish	14.00
One 15-inch Eastman trimmer	13.50
Twelve copies, Manual of Style, University of Chicago Press	32.50
One Klera-desk	3.70
Total cost of equipment	$759.81

[Note: The Union has a large stock of Transactions of past years available for sale, but these are carried as without value in the inventory.]

SPECIAL ANNOUNCEMENTS

Nomination and election procedures--The Committee on Nominations is preparing its report on procedures for implementing the Statutes and By-laws with regard to elections by mail ballot. An announcement of the procedure adopted by the Executive Committee will appear in the December issue of the Transactions, following which steps for the elections by mail ballot to be held in the first half of 1947 will be taken. The terms of all elected officers of the Union and all of the Sections expire June 30, 1947. It is expected that elections will be completed before the Annual Meeting of 1947, and announcements of results will be made at that time. Be sure to consult the closing page of the December issue for further word on this matter.

Changes of address--Many changes of address have been received in the last few months, but the return of Transactions and other communications indicates that AGU has not been entirely successful in maintaining an up-to-date file of addresses of the membership. If you have recently changed your address, or anticipate a change, please advise the Executive Secretary of the AGU promptly, at 5241 Broad Branch Road, N. W., Washington 15, D. C. Experience has proven that the use of two addresses for a member, or an attempt to withhold certain classes of mail, forwarding others, is confusing and costly.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 27 DECEMBER 1946 Number VI

ASTRONOMIC CONTROL FOR WARTIME MAPPING OF NORTHERN CANADA

Noel J. Ogilvie

Introduction--In the early summer of 1610, the first vessel sailed into Hudson Bay in search of a northern sea route from England to Cathay. In the following spring, Henry Hudson, the ship's intrepid master, beset by a mutinous half-starved crew, was cast adrift in a small open boat to perish from cold or starvation. Although the tragic details of his untimely death were never made known, Hudson's dauntless spirit lived on to inspire the many explorers who followed in his wake.

From 1612 to 1640, voyages led by Button, Bylot, Baffin, James, and Fox followed at intervals of a few years. But a much more active period of investigation of the Canadian Northland dates from Samuel Hearne's expedition to the Coppermine River in 1769. From then onward, over a period of a century and a half, the geographical secrets of the North have been revealed little by little at the cost of many lives and much human suffering. The austere and inhospitable country, as if resentful of the presence of intruders, seized every opportunity to crush its victims in an icy grip or dash their vessels on a rock-bound coast.

As the early investigators were handicapped by the lack of instruments, modern technical knowledge, and scientific inventions, the geographical information which they secured at great cost was not usually of a precise nature. The maps and charts embodying their new discoveries were seldom based on accurate observations. In general, the latitudes of strategic points shown on their maps were much more accurate than the longitudes. The delineation of the topographical features was usually in the form of crude sketches or drawings which were not based on ground surveys.

In more recent times, the Canadian Arctic Expedition to the Beaufort Sea in 1913-1918 marked the beginning of surveying and mapping in the North by accurate position observations and ground surveys. From 1918 to 1939, other ground surveys of relatively small extent, around trading posts and police stations, were made at widely scattered points by the Department of Mines and Resources. Up to the beginning of the Second World War, however, little planned mapping by modern survey methods had been done in the Arctic or Sub-Arctic regions of Canada.

Wartime mapping requirements--The Japanese attack on Pearl Harbor and the entry of the United States into the War resulted in a rapid development of military and civil aviation in northwestern Canada. The bomber route to Russia, the Canol pipe line, and the Alaska military highway provided the stimulus for the production of better maps of that area. About the same time, the development of the air routes to England by way of Newfoundland, Labrador, Greenland, and Iceland created a demand for aerial maps of northeastern Canada and Labrador.

The production of new maps by aerial photographic methods became the joint concern of Canadian and United States authorities. The areas adjacent to the new developments were given priority in mapping. Gradually, the areas mapped were extended farther north, east, and west to include a considerable part of the unmapped portion of continental Canada.

Establishment of ground control--In the spring of 1942, the Geodetic Service of Canada was called upon to provide astronomic ground control for this extensive project of aerial mapping. Lacking sufficient instruments and trained personnel, new instruments were secured wherever possible, and additional men were trained to carry on the field work. From 1942 to 1945, inclusive, four parties were sent out each summer to establish ground control over unmapped areas from Labrador to the Alaska boundary. Up to the end of 1945, a total of 215 stations was established during the short field seasons obtaining in these northern latitudes.

Types of country covered--As the vast extent of country over which the work was carried on was 2400 miles in width by 500 miles in depth, it follows that a general description would not be applicable to all parts. Five distinct types of country might be mentioned--the sparsely wooded rocky plateau of northern Quebec east of Hudson Bay; the low-lying muskeg and tundra area between the west coast of Hudson Bay and the Mackenzie River watershed; the Mackenzie River

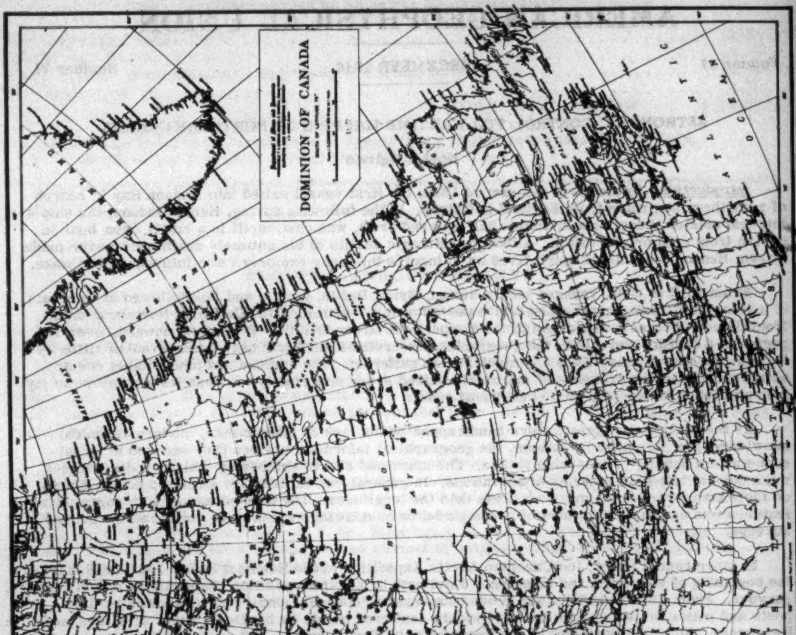
DOMINION OF CANADA
GREENLAND
DAVIS STRAIT
HUDSON BAY
ATLANTIC OCEAN
PACIFIC OCEAN

Fig. 1—Map of Northern Canada showing distribution of astronomic ground control stations up to the end of 1945

watershed, much of which is heavily wooded; the mountainous areas of the Yukon Territory and northern British Columbia; and the open plain in the northern part of the Yukon which dips towards the Beaufort Sea.

Transportation--Although the field parties used both boats and planes for transportation, by far the greater part was by plane. In the first two years of the operations, pontoon-equipped Fairchild and Norseman aircraft, provided by the Royal Canadian Air Force and commercial airlines, were employed.

During 1944 and 1945, a large Canso amphibious plane was supplied by the R. C. A. F. (see Fig. 2). The large carrying capacity of this type of aircraft proved very helpful in establishing new base camps and freighting in gasoline and supplies. The transportation of the sub-parties from station to station was made by Norseman planes.

Due to the hazards of landing on the shallow, rock-infested waters of the west coast of Hudson Bay, some of the ground stations located in that area could not be reached by plane. In such cases, an auxiliary schooner of about ten tons displacement was secured from one of the fur-trading companies operating in the locality.

Organization of the field parties--Each party consisted of an observer and a helper, who acted as recorder, cook, and general assistant. The latter usually devoted some of the daylight hours at each station to the taking of magnetic observations.

The aircraft personnel who lived at the base camps comprised the officer in charge of flying, three pilots, six mechanics, two navigators, two radio operators, a meteorologist, and a cook. As the observing parties carried portable radio transmitters, two-way contacts were usually made each day between the base camp and the outlying camps of the observers.

Method of observation--As the mapping project called for speed, it was decided that only one clear night could be spent at each station. It was also concluded that the semi-precise method of position fixation, by observing five or six stars at a fixed altitude in each of the northeast, southeast, southwest, and northwest quadrants, should be the method used. This decision was, to a large extent, obligatory, due to the lack of sufficient equipment for making precise determinations. It was also realized that precise determinations of position would serve the purpose little better than semi-precise values, as the station anomalies, because of the deviation of the vertical were liable to exceed greatly in size the errors in the astronomical fixations.

Instruments used--Two types of precise theodolites were used for making the star observations--the 5.5-inch Wild instrument, manufactured in Switzerland; and the 5.25-inch Tavistock, manufactured by Cooke, Troughton, and Simms in England. For latitudes up to 64°, a fixed angle of 60° was used. North of latitude 64°, the scarcity of stars in the northern quadrants necessitated the use of a fixed angle of 45°

The times of star transits were usually recorded on an electric chronograph. Both the drum- and pricker-type instruments were used. The latter, being both light and compact, was found most suitable for plane transportation. Occasionally, stop watches were employed instead of chronometers, with no apparent lessening of the accuracy of the fixations.

Radio time signals--The radio time signals used for the longitude determinations were received on small, three-tube portable receivers, powered by dry batteries. Signals from the Dominion Observatory at Ottawa, the Naval Observatory at Washington, the Bureau of Standards station WWV, and the naval station NPG at Mare Island, California, were all used from time to time, depending upon which station gave the clearest and strongest signals.

The accuracy of the fixations--The geographical positions were computed from sets of four stars each--one in each quadrant. From a normal night's work, sufficient observed stars were available for an arrangement of five or six sets, each giving an independent value of the latitude and the chronometer correction. The average probable error of the mean result from a night's work was of the order of ± 0.75 second of arc.

Local ground control--The establishment of each ground control station was completed by making a few survey ties to prominent topographical features in the vicinity. Sufficient information was required in each case to permit the construction of a local map so that the position of the station could be pin-pricked at a subsequent date on an aerial photograph. Prominent points of land, the ends of bays, the junctions of streams and lakes, small islands, and the sharp turns in rivers were tied in, where possible, without the expenditure of too much time.

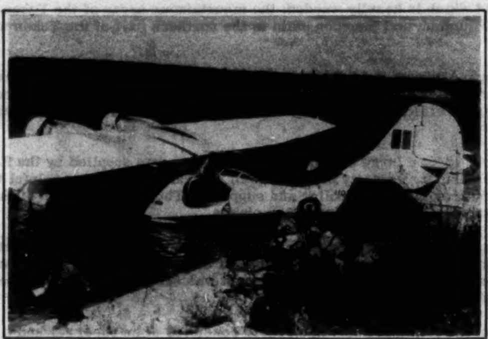

Fig. 2--The "Canso" supply aircraft at Nueltin Lake, Northern Manitoba

Fig. 3--Station marker, with whitewashed cross for recognition from the air, Southampton I

The precise Wild and Tavistock transits used on the astronomical work proved very useful in determining the distances to the topographical features. To save time, it was necessary to use poorly-shaped, elongated triangles. A base line 200 or 300 feet long was usually measured on a distant island or point and the subtended angle read at the astronomical station to the nearest second. The accuracy of the lengths determined by this method was quite sufficient for the purpose for which they were required.

Aerial photography--Before leaving a station, a series of aerial photographs was taken of the local area. The hand-operated camera, originally used for this purpose, had a five-inch focal length and a shutter speed up to one four-hundredth of a second. The size of the film unfortunately was only 2.25 × 3.25 inches, which proved to be too small. During 1945, larger cameras taking a 5 × 5-inch film were tried out with much more satisfactory results. This model had a focal length of five inches, a 60° angle lens, and a maximum shutter speed of one three-hundredth of a second.

Productivity of the North--Apart from oil, minerals, timber, fur, and fish, the North has proved itself capable of a surprising horticultural and agricultural production in the more sheltered valleys. At Arctic Red River in latitude 67°24′, the garden of Mr. Clark, an independent trader, is famous for its cabbages, cauliflowers, turnips, peas, and potatoes. It is a revelation, in general, to see the practical possibilities of producing garden crops north of the Arctic Circle.

At Aklavik, the miniature metropolis of northwestern Canada, located in latitude 68°13′ on the west channel of the Mackenzie River delta about 50 miles from the Arctic Coast, the North meets the South. This town serves as a transfer point for freight from the river boats of the Mackenzie to the seagoing schooners which serve the isolated points along the Arctic Coast. At Aklavik is found a busy town, where primitive Arctic life blends with modern civilization.

During August, families of Eskimos come in by schooner from Banks Island and keep the trading posts busy bartering trade goods for the winter fur catch. Although not a part of the customary Eskimo diet, fresh milk may be bought at Aklavik. In spite of the long winter seasons, a dairy herd is successfully maintained at this northern point. Fields of oats, growing close to the Church of England mission, indicated that some of the cattle feed could be produced locally.

The restaurants include both whites and Eskimos among their clientele. It is said that some of the natives, newly arrived in town with the proceeds of their winter fur catch, are eager to patronize the cafes and treat their families to a white man's meal at a dollar and a half per plate.

Dawson presents a curious combination of the past glories of the gold rush of 1898 and the present day activities of catering to the needs of a dwindling gold industry. The presence of several excellent stores, where everything necessary to modern life is displayed for sale, is convincing evidence that the term "ghost town" would not be applicable to Dawson. However, a stroll through the streets presents to view many abandoned stores, warehouses, hostels, and dance halls, which hummed with the exuberant life of the gold rush. In those days, Dawson had a population of about 25,000 people. Today the population totals about five or six hundred souls.

Too much cannot be said of the courtesy and service that is extended to strangers in Dawson. The custom which prevails amongst young and old alike of both sexes in greeting strangers when passing on the street, is evidence of the friendly spirit generally prevailing in the North.

In the summer, Dawson in latitude 64°03′ gets about 18 hours of sunlight per day. In the fertile soil at the rear of the waterfront, luxuriant garden growth includes lettuce, cabbages, potatoes, and peas. Hothouse tomatoes were also observed at one or two residences.

For years, the gold production of the Dawson District has been progressively declining. In the outlying placer areas, a number of large dredges still operate in the summer months, giving employment to about 1000 men.

Old Crow, which is located at the junction of the Porcupine and Old Crow rivers in latitude 67°34′, has a R. C. M. P. post, a mission of the Church of England, and three or four trading establishments. A large part of the Indian population gains its livelihood by trapping the muskrats which abound in the locality known as the Old Crow flats. This area, which is a mass of lakes and ponds draining into the Old Crow River, lies about 100 miles north of the Arctic Circle. At a ground control station north of Old Crow village, small trees were found growing despite the fact that in the middle of the summer the ground is frozen solid to within six inches of the surface.

In his official reports, B. J. Woodruff, the engineer in charge of the 1944 and 1945 operations, has made available a number of items of general interest not directly pertaining to the survey work. His description of the wonderful color effect as seen from the air in flying over the Old Crow flats is worthy of mention.

"During our season's work, we had viewed a variety of scenery over both mountain and valley, but the colors presented by this particular stretch of country were beyond description. As we flew southward, cutting across the sinuous windings of the river, the adjacent muskeg varied in color from green to yellow, to brown and black. Some patches suggested huge alligator skins, tanned and stretched out to dry, while other areas, lighter in shading, were dotted with small birch or poplar trees dressed in brilliant summer green."

Chesterfield, on the northwest corner of Hudson Bay, with its police post, Roman Catholic mission and hospital, Government radio station, and Hudson's Bay Company post, is a community of 20 to 30 white people, while the native population includes the few individuals permanently attached to the trading post and hospital and the hunters and their families who generally arrive at Christmas and Easter to join in the religious festivities, as well as to trade and catch up on the local news.

At Chesterfield, officials of both the Roman Catholic mission and the Hudson's Bay Company maintain summer greenhouses where lettuce, radishes, and other vegetables are grown. In spite of the lack of suitable soil, and hampered by a short growing season, the glass gardens produce considerable fresh material for salads, which is much appreciated after living for months on end on dried or canned vegetables.

Animal and bird life--Probably the greatest revenue producer of the North is the Arctic white fox. Its habitat is extensive, covering most of the area north of the tree line. Its skin is the main item of barter, and with the Eskimos it is considered almost as a medium of exchange.

The barren-land caribou is also an important animal in the native economy. In the area lying north of the tree line between Great Bear Lake and Hudson Bay, great herds of these animals are to be found. Living almost entirely on moss and grass, they prosper on the so-called "Barren Lands" where moose and deer cannot exist.

In the area adjacent to the Dubawnt River in latitude 62°, a great herd comprising twenty or thirty thousand head was seen in 1945. The same day, about 100 miles to the west, another observation party had so many caribou around their camp as to create a hazard to both instruments and equipment. At the R. C. A. F. base on the Kazan River, latitude 61°34', the local Eskimos were able to drive a number of animals into the camp before killing them. Hardtack biscuits were exchanged with the natives for the caribou meat.

In the central and western sections, bird life is not abundant. Robins were observed in the southern part, while ptarmigan were seen at most of the stations clear of the treed areas. Geese, ducks, and other aquatic birds were seen, but not in large numbers.

When travelling by water, some new aspects of the country's resources are revealed. From the sea, the natives get seal, which forms the main food supply, and, in addition, gives material for clothing, footwear, oil for heating, and leather for dog-team harness and harpoon tackle.

In 1942, the geodetic party, in crossing the entrance to Foxe Basin by boat, encountered a herd of walrus. These large animals, some of them weighing over a ton, had come down from the north with the ice. The walrus provides an excellent food supply for the Eskimos and their dogs. The ivory tusks of the walrus provide material for native handicraft work. Carved models of polar bears, seals, boats, and cribbage boards are made from the ivory and sold at good prices to the traders. Some of the natives exhibit an amazing talent in the production of such articles.

Fish were found in all the deeper lakes, and many fine specimens of lake trout were caught by casting from the shore. The Arctic char, a fish resembling the salmon trout, can be found in most of the northern waters.

Eskimo life--Comparatively few Eskimo groups were encountered. However, at the R. C. A. F. base on the Kazan River, a steady flow of native visitors was received. Before approaching the white men's camp, the Eskimos usually parked their women and children at a distance of several miles. It has never been made known whether the women were lacking in curiosity, overwhelmed by timidity, or merely conforming to their ideas of propriety in avoiding the presence of strange white men.

In general, the Eskimos are cheerful, happy, and make excellent guides on overland trips. They are intelligent, hardworking, and efficient in securing food supplies of fish and game. On their long treks away from the trading posts, the game is sometimes scarce and conditions of privation and semi-starvation obtain.

The Eskimo community life is well organized. While the men are engaged in the pursuit of game, the women and children busy themselves with the preparation and drying of meat and blubber. Caribou skins are stretched out to dry, while seal skins are immersed in water, where a rotting action helps in the detachment of the unwanted fatty coating. Seal oil is extracted from the blubber and stored in skin or metal containers.

At one geodetic station, some visiting Eskimos witnessed the two-way radio phone contact between two observing parties a hundred miles apart. Several of the natives were permitted to talk to each other on the radio. At the conclusion of the contact, one Eskimo asked, "How many fox skins for a radio that will work in an igloo?"

It is not surprising to find that in some years, when the white fox are plentiful, the good hunters may earn in exceptional cases up to three or four thousand dollars. These earnings are usually spent with thoroughness and despatch on trade goods obtainable at the nearest store. Food supplies, rifles, traps, outboard motors, gasoline, and ammunition are the commodities in greatest demand.

The R. C. M. P. posts, the mission stations, and the trading posts all keep a supply of medicines and surgical dressings. Trained in first aid, the white residents do a great deal to help the natives when sickness befalls them. As the distances between posts and settlements are large, vast areas of territory, however, are isolated from any settlement. Anyone seriously injured or sick far from a trading post must be rugged indeed to survive the lengthy journey necessary to obtain aid.

The whole area surrounding Hudson Bay is rich in historical associations, which have been reflected in the names given to the natural features. In some cases, the passage of time has buried the story until it is often wondered what particular mercy prompted the name of "Bay of God's Mercy," or what high hope of success or survival from impending disaster was associated with the naming of "Cape Hope's Advance," or where the "welcome" of "Roes Welcome Sound" originated. In other cases, the names of the early explorers and their patrons have been retained to the present time.

Full credit must be given to the field engineers of the Geodetic Service of Canada and flying personnel who participated in the wartime mapping of northern Canada. Braving cold, unfavorable living conditions, and the hazards of flying over an unmapped country, they did not all return from the North. In the summer of 1945, F/O Leslie Wheatcroft and F/O Douglas Shackleton, of the R. C. A. F. transport unit, were drowned in the icy waters of Nueltin Lake. Like the intrepid Henry Hudson, they gave their lives in the interest of geographical research.

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Transactions, American Geophysical Union Volume 27, Number VI December 1946

SEISMIC WAVES FROM ATOMIC BOMB TESTS

B. Gutenberg and C. F. Richter

(Contribution no. 395, Balch Graduate School of the Geological Sciences,
California Institute of Technology)

Registration of seismic waves from atomic bombs provides a direct check on accepted travel-time curves. The Baker Day test at Bikini on July 24, 1946, U. T., was recorded at eight stations by short-period Benioff vertical-component seismometers. Only longitudinal waves (P) appear; no transverse waves or surface waves have been found. Figure 1 shows the seismogram at Mount Wilson; the others are similar.

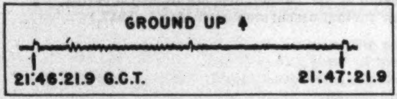

Fig. 1--Bikini atomic bomb test, July 24, 1946 (U. T.), Mount Wilson short-period vertical component Benioff seismogram. Original length of minute 60 mm

We are indebted to the United States Coast and Geodetic Survey for a copy of the Tucson seismogram and to D. S. Carder of the Coast and Geodetic Survey for copies of those at Boulder City, Pierce Ferry, and Shasta Dam.

The Office of Naval Research has kindly furnished the following data: Time of detonation, $21^{h}34^{m}59^{s}.76 \pm 0.1$ sec, July 24 (U. T.); position, 11°35′N, 165°30′E. Results are shown in Table 1.

Table 1--Results of atomic bomb tests

Station	Distance	Time of P	Travel time	O - C
	°	h m s	m s	sec
Shasta Dam	69.0	21 46 07.5	11 08	- 4
Tinemaha	72.2	21 46 28	11 28	- 3
Mount Wilson	72.4	21 46 28	11 28	- 4
Riverside	73.0	21 46 31	11 31	- 4
Palomar	73.5	21 46 35	11 35	- 3
Boulder City	75.0	21 46 42	11 42	- 4
Pierce Ferry	75.6	21 46 47	11 47	- 3
Tucson	78.6	21 47 04.5	12 05	- 3

In the column O - C are residuals obtained by subtracting from the observed travel times those calculated for a surface focus [see "References" at end of paper, GUTENBERG and RICHTER, 1939, p. 97]. These residuals are probably mainly due to the exceptional structure of the Pacific basin. The travel times referred to assume origin in a continental region. Supposing continental rocks to be absent in the Pacific basin, rough calculation indicates that travel times to large distances should be about two seconds less. Accordingly, the zero of the standard travel time curve is probably correct within a second or two. This confirms the result for the New Mexico test of 1945 [GUTENBERG, 1946], where the origin time had to be calculated from the arrival of the direct wave $\bar{P}$ at Tucson, and where the observed arrival of Pn at Tucson, Palomar, and Riverside was about one second later than expected. Recorded amplitudes of P from the Bikini test are about equal to those of a shock of magnitude 5.5 at the same distance.

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Transactions, American Geophysical Union Volume 27, Number VI December 1946

MICROSEISMS, THE UNKNOWN

L. M. Murphy

Abstract--A review is given of the theories on microseisms as to their origins, causes, and characteristics, and the results obtained by the investigations of various seismologists. The demand for more experimental data is emphasized, together with many suggestions for obtaining a better understanding of microseisms.

It is well known to all seismologists that microseisms have been a source of investigation and speculation for over a half century. During this time very little new experimental data were obtained aside from ordinary measurement of amplitudes and periods of microseisms on regular teleseismic records. About 1937, the first real experimental research was undertaken at Göttingen and was further advanced in 1938 at St. Louis and during the War under the Naval meteorological microseismic program. These recent investigations are the only sources for experimental data on the origin and nature of microseisms. As will be shown in this paper, even these data are very incomplete and leave many questions for debate by those thoroughly acquainted with microseisms.

In the work of microseismic investigators various theories have been expounded as to their cause. BANERJI [see "References" at end of paper, 1935] holds that Rayleigh waves are set up at the bottom of the sea in the form of a train of waves which may be maintained by the monsoon currents. GHERZI [1924] believes the air pumping caused by typhoons produces microseisms if periodic vibrations exist in low pressure areas over the oceans. BRADFORD [1936] and Klotz maintain that the relatively rapid pumping of the air on the forward side of a low pressure area will produce microseisms. The Göttingen school upholds the surf theory as the main source. It is therefore obvious that seismologists will continue to theorize and speculate until some person or organization has the foresight and facilities to confirm theory with experimental data.

As to the origin of these microseisms, RAMIREZ [1940] holds: "The focus or origin of microseisms does not seem to be a point, as is the first motion in earthquakes, but rather a region several hundred km in diameter." This he infers as a possible cause of the arrival variations of the same waves at two stations in a tripartite group. The evidence which LEET [1934] obtained "favors storm waves in large bodies of water as the cause, whether they beat upon rocky coasts or not." The relationship common to all nine cyclonic storms in the vicinity of New England which LEET [1934] studied, is that "microseisms result from the passage of a cyclonic center only when it is so located as to give rise over wide areas of the Atlantic to winds which can generate strong surf along the coast."

WHIPPLE and LEE [1935] expressed "the opinion that in considering the transmission of waves to the sea bottom the compressibility of the water must be allowed for, and that disturbances travel downwards or obliquely with the velocity of sound in water." An important fact in their explanation is "that if the disturbance is generated by impulsive pressure at a point, motion begins at the same time at all distances though the surface waves travel with finite velocity."

In recent investigations GILMORE [1946] says "the results of storms in the Gulf of Mexico suggest that the microseisms are produced by some force within the hurricane itself and that they are then transmitted to the ocean bottom and thence through the ground to the seismograph."

In all of these comments on the origin it is interesting to note the lack of any data obtained near the source, especially when over the oceans. Recently several methods were suggested for on-the-spot determination of storm pressure readings over the water and pressure readings in the water at various levels until the sea bottom is reached. At this position a special seismograph would be set up to record the Earth motion while the storm is passing above. It would also be interesting to see the influence of the storm passing over an area where a microbarograph is in operation. This may offer some additional evidence as to the origin of microseisms. Of course, this is an expensive undertaking. But with the cooperation of all interested geophysicists, including those of the Navy, the results obtained would soon pay for themselves.

Because of the lack of information concerning the origin of microseisms, the nature of the microseismic wave has been debated by many. RAMIREZ [1940] concludes that "the Rayleigh theory and the observed characteristics of microseisms seem to agree fairly well except for the motion across the direction of propagation . . . These waves may be independent waves of the same type . . . due to refraction and reflection . . . Finally, it may be that the waves . . . form part of the motion of the particle . . . "

LEE [1932 a] mentions "the possibility that the movements might consist of Rayleigh waves and Love waves superimposed has hitherto been overlooked." However, his results tended to show that Love waves may be neglected. Later WHIPPLE and LEE [1935] state, "The microseismic waves are Rayleigh waves and are subject to changes of type according to local geological conditions." GUTENBERG [1931] maintains that these waves are of the Rayleigh type.

LEET [1934] states, "Longitudinal and transverse waves were identified. No Rayleigh waves were found. Nothing in the analysis shows whether the transverse are surface or body waves."

GILMORE [1946] from his latest observations says "the waves are sometimes linear with frequent variations of direction of motion and appear very often to be either circular or elliptical."

As may be seen, there still is not complete agreement among the investigators. Future work should explain the exact type of waves and also reveal the influence of transmission of these waves through various layers, especially the effect of continental layers upon microseisms.

In analysing the various microseisms received at a number of teleseismic stations, a great many characteristic waves are found and until now there have been no thorough studies made of them. In connection with the amplitude of the waves, LEET [1934] says "It has been pointed out by many writers that there is a tendency for period to increase with amplitude in microseisms . . . Exceptions to this may be noted . . . the most common one being the persistence of long periods late in a storm as amplitudes decrease." LEE [1932 b] found that "There is generally an increase in the amplitude of the microseisms as the period lengthens." Later he states [1932 b] "The absolute amplitude of the microseisms varies over a wide range, depending upon the locality and geological structure." GILMORE [1946] claims that "depth of water (very shallow, probably three ft) has considerable influence on the size of the amplitudes. Also geological discontinuities have tremendous influence on the propagation of the waves." Most of these studies are of a general nature and are usually expressed in the form of a ratio between the two horizontal components and possibly a correlation with distance to the storm center.

There has not been a very exhaustive study of the variation of periods in microseisms due to numerous causes. GUTENBERG [1931] mentions that "irregular waves with very much shorter periods resulting from windstorm or surf on the local coasts, or still shorter waves caused by rains . . . are frequently superimposed on the normal microseisms." RAMIREZ [1940] found the periods (3.9 sec to 4.1 sec) shorter in summer than in the winter (4.0 sec to 5.5 sec). It is interesting to note that the periods of microseisms due to hurricanes have the same approximate period as those produced by extra-tropical lows.

There has been some comparison made of the relation between the periods and amplitudes under rather limited conditions. Gherzi, a number of years ago, made a very careful study of the characteristics of microseisms under numerous meteorological conditions. Using Galitzin records he found for a typhoon about 800 km away that there was a regular build-up (four to eight sec periods) to a maximum and then a gradual decrease as the storm moved away from the station. This is exactly the same as the hurricanes in the West Indies. Slightly cold weather and a wind of force seven (Beaufort) produced long-period waves of ten to 25 sec with rather large amplitudes and short-period waves of three to four sec superposed. With a very intense cold and light breeze blowing there were long irregular periods of 20 to 30 sec with three or four sec waves superposed which are the normal microseisms. In the case of a typhoon greater than 1000 km smaller amplitude waves were produced, but there were chains of rather regular period groups. There are also waves with rather long periods, greater than two min, of which there are numerous explanations offered although the origin is not thoroughly understood.

In the case of a cold front in Florida, GILMORE [1946] found very irregular and short periods possibly produced by wind or slight surf.

All of these meteorological conditions have a definite influence on the period of the microseismic waves. At the stations with the more sensitive short-period instruments the 0.1 sec to one sec microseismic wave is a dominant type which should be thoroughly investigated.

The work of Gherzi and others should be extended to more regions and made more complete. Although there has been no evidence so far that a cyclone produces any microseisms, there also have been no records obtained while a storm passed directly over a seismograph. Because of the width of a cyclonic path and the nature of the motion of its center there may not be any microseisms produced. But this should be disputed by positive evidence.

Possibly because of the lack of instrumental data from known positions of storms, there have been practically no studies made correlating the intensities of a storm with the corresponding microseisms. This will require a rather intensive study because of the number of variables involved in a storm. Before a microseismic-meteorological program can become entirely satisfactory in giving intensity evaluations, such factors as the general position of the low as well as the width of the storm center, the velocity of the storm, the influence of the depth of water beneath the storm, and some information on the geological units involved should be very well known.

Another factor which ordinarily is not difficult to obtain is the velocity of wave motion. This has been undertaken by recent investigators and rather large variations have been observed. According to KRUG [1937] for the normal microseisms of four to eight sec the velocity is 1100 ± 200 m/sec, which appears rather low. RAMIREZ [1940] found very good correlation in the few storms he analysed and obtained 2.67 km/sec as a mean value. In the most recent investigation by GILMORE [1946] he has a wide range of values at three positions; at Guantanamo Bay on coral ledge resting on partially consolidated marine sediment, 2.6 km/sec; at Roosevelt Roads, Puerto Rico on solid rock foundation, 4.0 km/sec; and at Richmond, Florida on partially decomposed coral rock, 3.25 km/sec. With these wide ranges it becomes imperative to undertake a more complete investigation of all regions where tripartite stations are set up. Obtaining these more accurate data will not only contribute to a greater understanding of the geological structure in these regions but also will improve the travel-time curves for teleseismic work, which are now very inadequate and are becoming more so with the development of better teleseismic equipment.

This tripartite station analysis of microseisms has been definitely effective in determining the direction of storm paths. LEE [1935] measured phase differences to obtain a general direction, but RAMIREZ [1940] and GILMORE [1946] have been able to trace a storm's azimuth quite accurately along its path. How exact a position may be obtained is still open to question. At the present time, with such an insufficiency of good data pertaining to microseisms, there may be an error of several degrees in the exact location of a storm center.

An outstanding peculiarity about which little or nothing has been said is the phenomena of recording maximum microseismic amplitudes many hours (12 to 24) after the storm has passed the sites of the recording seismographs. This is true not only for island stations such as Bermuda and San Juan but also for stations on the continent such as St. Louis, Chicago, Ottawa, and Weston.

Considering all of the data which are known and which must be known before microseisms are removed from the realm of the unknown, it is obvious that the instrumental problem is the greatest handicap to microseismic progress. If the elaborate experimental setup required in the tripartite arrangement cannot be simplified, this research is beyond the financial limits of the ordinary research investigator. It seems very probable that it can be further simplified and still increase the accuracy of the results obtained. For routine study of storms, after much of the technical information has been discovered, it appears that a good high magnification vertical instrument could replace the horizontals and eliminate the routine setting of the instruments to coincide approximately with the storm azimuths. Also an instrument with variable periods would assist considerably in the analysis of the period phenomena. Further investigation and development of visible recording seismographs would aid greatly in fostering a more widespread interest in microseisms and would also greatly reduce the cost of operation. The latter point is very important to many of the regular teleseismic stations and would exclude them from this extra investigation if the cost were to place an additional financial burden on them. Further work should be done to determine the minimum distance between the stations of a tripartite group. This is very important if this program is to spread to many of the present teleseismic stations which have limited areas on which to operate.

Once these data are recorded at hundreds of stations, there is the problem of transmitting them to a central office for complete analysis as the United States Weather Bureau does in the case of its daily analysis. If radio transmission or a system such as teletype were possible and were developed, it would provide a new and valuable tool in weather forecasting even outside of tropical areas where present interest is centered exclusively on hurricanes.

In reviewing the progress made in microseisms over more than half a century it may be said that a more definite knowledge and understanding of them were obtained during the past six years

than in any previous time. It is also firmly desired that much more experimental evidence in each phase of the microseismic research be obtained. This will eliminate much of the speculation which has been so detrimental to progress in the past and will reveal the potential value of microseisms in solving a number of important meteorological and geological problems.

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AN INTERPOLATING CONTACTOR FOR SIXTEEN-POINT RECORDING OF WIND DIRECTION FROM A STANDARD EIGHT-POINT WIND VANE

Ronald L. Ives

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Abstract--A relay-type contactor designed to make a contact closure corresponding to each single closure of the contacts of a standard eight-point wind vane; and a discrete contact closure independent of the previous series, corresponding to each "bridged" condition, when two adjacent contacts are closed simultaneously, is here outlined, with maintenance and operational data.

Introduction--Continuous recording of wind direction by use of chart recorders, such as the Selsyn (unlimited points), or a resistive recorder (eight points) [see "References" at end of paper, IVES, in press], imposes no serious technical difficulties. Recording of directions to 16 points from a standard eight-point wind vane with 180° direction ambiguity is possible by use of a bridged resistive ring [GRINNELL, 1945], or several other devices of greater complexity. Direction ambiguity may be eliminated by use of "polyphase" resistive circuits.

Isokinetic or isotemporal recording from an eight-point wind vane (standard, such as Friez type 363-C) is subject to quite serious trouble from count duplication because of contact bridging. Methods of obtaining eight-point periodic recordings on visible or printing counters without this undesired count duplication have been described elsewhere [IVES, 1946]. Desirability of securing space- or time-controlled periodic direction recording to 16 points without count duplication due to contact bridging led to development of the interpolating contactor to be described here. This contactor is suitable for use with a battery of visible or printing counters; for operation of a modified dot-printing Micromax recorder (chart interpretation extremely laborious); or, without the time or space control, for 16-point series-resistance continuous recording of wind direction without ambiguities.

General theory--Sixteen-point recording without duplication of counts requires that only one of the 16 counters, corresponding to the 16 directions, be in circuit at any given time. With a conventional wind vane, eight of these wind directions are indicated by closure of a single contact; the remainder by closure of two adjacent contacts ("bridging"). By use of a battery of relays, counters controlled by closure of one contact alone are put in circuit as that contact is closed. Counters controlled by the bridging of two adjacent contacts are connected in circuit only when both of the contacts are closed, and adjacent counters, corresponding in position to and controlled by single contacts, are disconnected.

Circuit operation--The circuit of a part of the interpolating contactor constitutes Figure 1. As this is a repetitive circuit, only a part need be shown to demonstrate the principles involved. Operation of a typical portion is as follows: When the supply is energized but no connection is made from COM to any point, all relay armatures are in up position. When the contactor connects COM to K, and to K only, relay K pulls down, connecting counter K only in circuit through the center contact of relay K, the lower contact of relay KL, and the center contact of relay JK. Counter K now records each closure of the control relay contacts until point K is no longer connected to COM.

If the contactor bridges K and L, so that K, L, and COM are connected together, relays K and L pull down, closing all down contacts on all their circuits. This energizes relay KL, through the lower contact of relay K and the upper contact of relay L, pulling it down. Counter K is disconnected by opening of the lower contacts of relay KL; counter L is disconnected by opening of the center contacts of relay KL; and counter KL is connected by closing of the top contacts of relay KL. Counter KL now records each closure of the control-relay contacts until K and L are no longer connected together and to COM.

If the contactor moves toward L from its previous position bridging KL, so that L only is connected to COM, relays K and KL are de-energized and their armatures rise, disconnecting

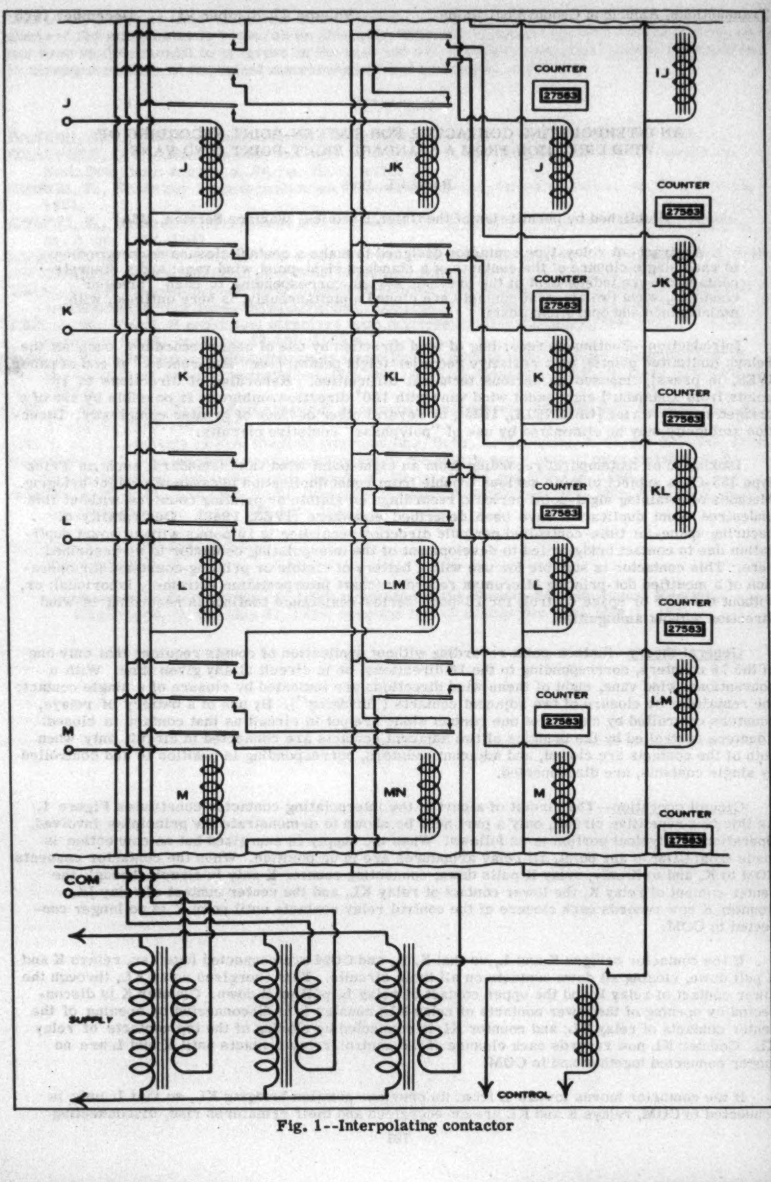
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Fig. 1--Interpolating contactor

counter KL from the circuit by opening of the top contacts of relay KL, and connecting counter L into circuit, by closure of the center contacts of relay KL. Counter L now records all closures of the control-relay contacts until conditions change.

The first-described sequence, K, occurs whenever any contact alone is connected to COM; the second-described whenever two adjacent contacts are bridged.

Performance and maintenance--When good grade components are used, service life of a contactor of this type usually exceeds the factory rating of the components, provided systematic maintenance of the contacts and careful checking of the constants of all components is started immediately after the contactor is put in service. Immediate replacement of any component showing a marked change in electrical constants or indication of mechanical wear will prevent service interruptions at inopportune times.

Connection of a spark absorber, consisting of a resistor and condenser, across each relay and counter coil will extend the life of the contacts greatly and will markedly reduce radio interference in the general vicinity of the instrument.

Ultimate refinements--Equipment now developed but not now generally available, consisting of an eight-plate 16-target cathode ray relay, may soon replace the outlined electromechanical relay device. If the grid of a thyratron is controlled by each target of the cathode ray relay, a counter can be operated by the plate current, so that all interpolating and switching operations described above, with the exception of the control, are performed silently, without the use of moving contacts.

Conclusions--The interpolating contactor described here fills an immediate need for a device which permits 16-point recording of wind direction from a standard eight-point wind vane. Performance, if properly maintained, equals or exceeds that predicted from the rated life of the components. Replacement of this device by a noiseless electronic switcher, without moving contacts, may be possible within the next decade.

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THE ANALYSIS OF HORIZONTAL DIVERGENCE IN THE FREE ATMOSPHERE

Robert C. Bundgaard

The practical need for analysis of horizontal divergence--Upper-air analysis may be regarded as the examination of the manner in which certain surfaces in the free atmosphere stand to each other instantaneously and sequentially. It is the graphic portrayal of the relationships among the isobaric, isosteric, isothermal, isentropic surfaces, and the surface of constant geopotential. These surfaces describe geometrically certain physical quantities. Analytical relations among these physical quantities provide the means for obtaining two main objectives of upper-air analysis, namely, a kinematical and dynamical comprehension of (1) the horizontal atmospheric circulation and (2) the vertical atmospheric stability. Inasmuch as the atmospheric stability determines the conditions under which the air can achieve vertical displacement, the two objectives together concern the general motion of the air. The condition for the attainment of these objectives is careful choice of those surfaces, or layers between such surfaces, which satisfy economy and succintness in the analytical relations.

Under different conditions the two objectives of upper-air analysis vary. Consequently, the particular surfaces selected for optimum facility in analysis change accordingly. For an adequate analysis, then, it is necessary to stipulate the provisions under which it will be made.

One of the important conditions under which most of the present upper-air analysis techniques are applicable is the presence of relatively large land areas, and of contrasting air masses which are extensive and which frequently replace one another. The spatial and sequential variation in the layers and surfaces which geometrically represent the fields of the various physical quantities of the atmosphere, therefore, are prominent features. The inclinations of the intersecting surfaces with each other are large. Changes, with time, at any point in the temperature field are usually caused by five processes: (1) The non-adiabatic process of advection, which usually constitutes the principal factor in the heating and cooling; (2) the non-adiabatic process of radiation, which contributes least to the short-period temperature changes, except in the lower atmosphere over land surfaces; (3) the adiabatic process involving motion through the geopotential surfaces, which may become the dominating influence, especially in the upper atmosphere; (4) the adiabatic process involving motion on a constant geopotential surface through isobaric surfaces; and (5) no motion where the isobaric surfaces are changing with respect to the geopotential surfaces. This last process exerts greater influence in the upper atmosphere than at the Earth's surface, and is more important than process (4).

These conditions, which prescribe a particular methodology for upper-air analysis, exist in the extra-tropical latitudes. The compendium of present upper-air analysis techniques is applicable to them.

In the tropics and subtropics the conditions are very different. The ocean areas are large; the air masses are more homogeneous. In addition, the vertical distribution of the moisture field is extensive. As a consequence, the process of radiation (2) usually initiates the principal factor in pressure and temperature changes. The regulating influence of the sea surface on the air temperature in the lower atmosphere together with the presence of moisture as a radiative-absorbing substance in the middle atmosphere produces a large diurnal variation in temperature in the upper air. By day the lower part of the atmosphere has a tendency to be stable, and the upper part unstable. At night the reverse is true. The diurnal changes in temperature are greater than the changes due to the other processes. The inclination of the isopycnic surfaces with the surfaces of constant geopotential is not sufficient to provide for vertical motions by upslope motion over a more dense air mass. Instead, vertical motions are produced by mass convergence and divergence. Since the isobaric and isothermal surfaces nearly coincide with the surfaces of constant geopotential, the temperature variation over an isobaric surface, or a constant geopotential surface, is less than the diurnal variation and the slight instrumental and reduction errors. The delineation of the relation between the isobaric, isothermal, and constant geopotential surfaces is not significant, because these intersecting surfaces are only slightly inclined with each other. The interpretation of isobars or contour lines as streamlines for geostropic flow is generally not valid.

The application of extra-tropical procedures of analysis does not yield optimum comprehension of the tropical atmosphere. Consequently, it becomes necessary to develop a method of upper-air analysis for the tropics.

Under the conditions of the tropical atmosphere, the analysis for atmospheric stability becomes a more significant objective than the circulational analysis, as process (3) constitutes the principal factor of change. The type of analysis will depend upon the choice of surfaces and layers which give the most economical (as well as complete) analysis of stability. It is the purpose here to present and describe a method of upper-air analysis in accord with these introductory remarks.

The dependence of the field of vertical velocity upon the horizontal convergence and divergence of mass is the basic consideration for stability analysis in the tropics. If, as in Figure 1, there occurs during a given time interval a shrinking in the horizontal area A of a volume with constant mass M, there must be a vertical stretching of the volume if the density of the volume is to be maintained constant.

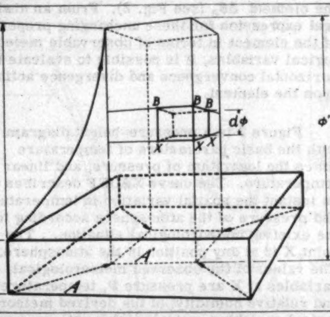


Fig. 1--Diagram showing effect of shrinkage of horizontal area for a constant volume

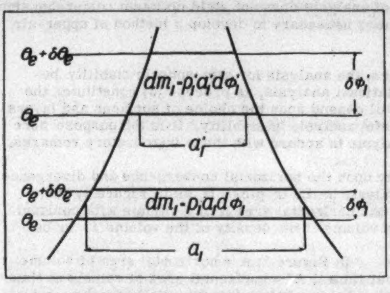
In Figure 1; A = horizontal area of volume at time t, A' = horizontal area of volume at time t + Δt, ϕ = height (geopotential) of volume at time t, ϕ' = height (geopotential) of volume at time t + Δt, ρ = density of volume, assumed constant $\rho A\phi = \rho A'\phi'$, and $(\phi' - \phi)/\phi'\Delta t = (A - A')/A\Delta t$. Under these circumstances vertical divergence ($\phi' > \phi$) accompanies horizontal convergence ($A' < A$) and vertical convergence accompanies horizontal divergence.

If the vertical convergence or divergence resulting from horizontal divergence or convergence is appreciable, the density of the volume does not remain constant but varies according to the particular thermodynamic process which the volume experiences as a consequence of its vertical motion. Furthermore, if the environment of the volume being considered is also undergoing a thermodynamic process different from the one experienced by the volume, the density of the mass contained changes accordingly, provided that the volume is properly considered to be constrained in no way by its bounding surface. Consequently, if the density of the mass is changed while a constant horizontal convergence or divergence is taking place, the amount of vertical motion of the mass relative to its initial position is determined not only by the magnitude of horizontal convergence and divergence it experiences but also by the amount its density changes. In order to avoid restricting the problem by the assumption that the density of the mass remains constant, an element of mass dm of the mass M is chosen (see Fig. 1) so that its density ρ varies as well as its horizontal area (a) and its thickness $d\phi$.

The greatest vertical velocity would occur at the level of non-divergence, the level where horizontal convergence changes to horizontal divergence. The upward vertical velocities increase with height below this level and decrease above the level of non-divergence for which horizontal convergence occurs below. Thus, the development of instability, clouds, and precipitation will have its greatest potentiality at the level of non-divergence. The degree of instability which will develop will depend on the amount of horizontal convergence and divergence, and the rate of change with height of the horizontal convergence or divergence. The extent of cloud and precipitation will depend upon the horizontal and vertical extent of the horizontal convergence and divergence as well as the moisture distribution.

A method of evaluation for horizontal divergence--It appears from these considerations that a proper method of weather analysis should include the determination of the intensity of horizontal convergence and divergence, of the rate at which fields of horizontal convergence and divergence change with height, and of the horizontal extent of such fields. This form of analysis is particularly profitable for use in the tropics, in the upper troposphere of extratropical latitudes, and in general for those conditions where advection does not account for the principal thermodynamic changes.

If the element dm of moist air can be displaced upward or downward without losing its identity, that is, without mixing with its environment, the process performed by the element is nearly


$\theta_e+\delta\theta_e$
$dm_1 \cdot \rho_1' a_1' d\phi_1'$
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$\theta_e+\delta\theta_e$
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Fig. 2--Constant characteristics of the element in terms of observable meteorological variables

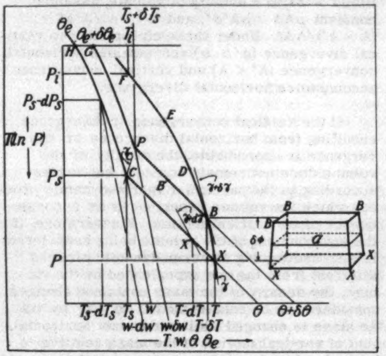


Fig. 3--Pressure-height diagram

adiabatic. As the mass dm of moist air ascends to its lifting condensation level the process is unsaturated adiabatic. For further upward displacement from the lifting condensation level the process is saturated adiabatic. The thermodynamic properties of the mass dm will change according to the particular adiabatic process which it undergoes. It will be shown that for both stages of the adiabatic process, there are three characteristics of the element which remain constant; namely, its mass dm (except for an insignificant change because of loss of moisture), its equivalent potential temperature θ_e, and the spatial variation of the equivalent potential temperature through the element $\delta\theta_e$ (see Fig. 2). From an analytical expression for these unchanging properties of the element in terms of observable meteorological variables, it is possible to evaluate the horizontal convergence and divergence acting upon the element.

Figure 3 is a pressure-height diagram with the basic parameters of temperature times the logarithm of pressure, and linear temperature. The curve XBDEF describes at an instant the spatial variation in temperature and pressure of the atmosphere according to the existing meteorological situation. The point X is at any position in the atmosphere. The values of the observed meteorological variables at X are pressure P, temperature T, and relative humidity; of the derived meteorological variables, actual mixing ratio w, condensation temperature T_S, condensation pressure P_S, potential temperature θ, equivalent potential temperature θ_e, lapse rate of temperature γ, and lapse rate of its condensation temperature γ_c; of the independent variables, time t (all units are in the meter-ton-second system). Spatial variation at the time t of these variables between X and any other point B of the atmosphere is designated by the geometrical symbol δ. At the time t the element under consideration is bounded by two surfaces at the points X and B, respectively. Its properties are the same as the above values, that is, P, δP, T, δT, w, . . . t. As the element ascends or descends, the change in its properties, that is, in these values of the element, is an individual variation determined by the adiabatic process which it undergoes. The curves XX'CH and BB'PG show the individual variation of the meteorological variables at the horizontal boundaries of the element dm occurring during the time interval subsequent to the time t. The individual variations during the time dt are designated by the differential symbol d. For example, as the image point X ascends to X', the individual variation in temperature is - dT.

The effects of horizontal convergence and divergence disturb the existing meteorological conditions of the atmosphere, with the consequence that at the time t + dt the curve XBDEF no longer represents the spatial variations of temperature and pressure for the element. Now, since X, Figure 4, has been considered to be any position at time t in the atmosphere, a column of the layer bounded by the surfaces P and P_i may be considered to be composed of a continuous series of discrete elements dm_i, i = 1, 2, 3, . . . one above another. During the infinitesimal period of time dt, these elements are displaced vertically through the distance $(V_Z)_i dt$, where $(V_Z)_i$ is the varying vertical velocity of each element dm. The volume of each element shrinks or expands vertically so that the column remains a continuous series of elements. During an element of time dt the individual variations in temperature and pressure and moisture of the elements dm_i will alter the spatial variation in temperature and pressure for the column of elements from XBDEF to some such curve as X'B'D'E'F' (Fig. 4). In Figure 4, the image point X of dm has moved to X' from X during dt. The properties of the element dm at the time t + dt are those of the atmosphere at the time and at the position reached by the element. Thus, the properties of the element can always be evaluated from the observed values of the atmosphere.

Since the dynamic thickness of the element is measured in the atmosphere, $d\phi = \delta\phi$ and $dm = \bar{\rho}\,\bar{a}\,\delta\phi$ where $\bar{\rho} = \rho + \delta\rho/2$ and $\bar{a} = a + \delta a/2$. Since the element dm is, strictly speaking, infinitesimal, its meteorological values, such as $\bar{\rho}$, $\bar{a}$, $\bar{T}$, $\bar{P}$, and $\bar{w}$, are not observably different from the values of these variables at its lower boundary, that is, at X. Therefore, $dm = \rho a\,\delta\phi$. For small displacements, the force of gravity does not vary significantly. Consequently, during the unsaturated stage XC, dm remains constant.

$$\left.\begin{array}{l} dm = \rho a\,\delta\phi = \rho' a'\,\delta\phi' = \ldots = \text{constant} \\ dm_1 = \rho_1 a_1\,\delta\phi_1 = \rho'_1 a'_1\,\delta\phi'_1 = \ldots = \text{constant} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ dm_i = \rho_i a_i\,\delta\phi_i = \rho'_i a'_i\,\delta\phi'_i = \ldots = \text{constant} \end{array}\right\} \quad \ldots\ldots\ldots\ldots \quad (1)$$

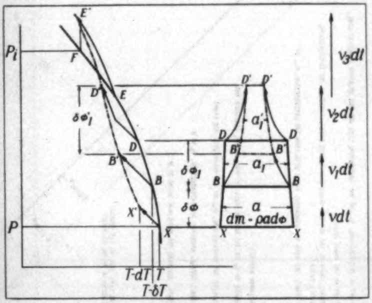


Fig. 4--Effects of horizontal convergence and divergence

If the saturated adiabatic process CH, Figure 3, is strictly adiabatic, then dm remains constant during its entire displacement. Equation (1) is true for the complete process of the element.

But the expansion of saturated air in a state P_s, T_s, where the subscript s refers to the symbol at the condensation level, is not strictly adiabatic, since some products of condensation may fall out immediately upon condensation. The total water content of the system is $wd(m_d)$, where w is also the maximum mixing ratio of the element at the state P_s, T_s, and $d(m_d)$ is the mass of dry air of the element. As the element continues to ascend and its image point moves along the curve from C to H (see Fig. 3), the amount $(w - dw)d(m_d)$ still remains in the vaporous phase as saturated vapor, while the amount $dwd(m_d)$ has condensed and appears as liquid water in the element. For a small upward displacement of the saturated air the vapor content $(w - dw)d(m_d)$ is very close to its initial vapor content $wd(m_d)$, that is, $dwd(m_d)$ is small. Therefore $(w - dw) \doteqdot w$ where $dw \doteqdot$ zero; and the mass dm may be considered to be constant during the entire adiabatic process it undergoes.

The spatial variation of equivalent potential temperature (see Appendix I) is

$$\delta\theta_e/\theta_e\,\delta\phi = [0.46/(1 + 0.46w)](\delta w/\delta\phi) + (L/c_pT_s)(\delta w/\delta\phi) + (Lw/c_pT_s^2)\gamma_c + (1/T)(\gamma_d - \gamma) \quad \ldots\ldots \quad (2)$$

where $\gamma_d = 1/c_p$, dry adiabatic lapse-rate of temperature; $\gamma = -\,\delta T/\delta\phi$ lapse rate of actual temperature; $\gamma_c = -\,\delta T_s/\delta\phi$, c_p = specific heat at constant pressure of dry air; and L = latent heat of evaporation.

For any adiabatic process which the element may undergo, the equivalent potential temperature at the lower boundary of the element and the change of equivalent potential temperature $\delta\theta_e$ through the layer of the element remain constant.

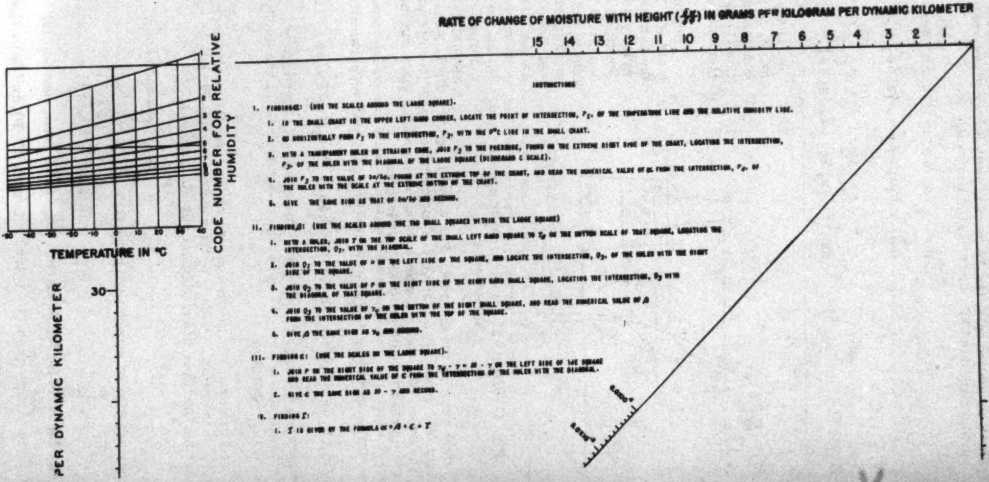
$$\delta\theta_e/\theta_e = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

By the ratios of equations (1) and (3)

$$(1/a\,\rho\,\theta_e)(\,\delta\theta_e/\delta\phi) = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Introducing in (4) for the factor $\delta\theta_e/\theta_e\,\delta\phi$ from equation (2)

$$a \times (\text{constant}) = [0.46/(1 + 0.46w) + L/c_pT_s](T/P)(\delta w/\delta\phi) + (LwT/c_pPT_s^2)\gamma_c + (\gamma_d - \gamma)/P \quad \ldots\ldots \quad (5)$$



INSTRUCTIONS

I. FINDING α: (USE THE SCALES AROUND THE LARGE SQUARE).

1. IN THE SMALL CHART IN THE UPPER LEFT HAND CORNER, LOCATE THE POINT OF INTERSECTION, P_1, OF THE TEMPERATURE LINE AND THE RELATIVE HUMIDITY LINE.
2. GO HORIZONTALLY FROM P_1 TO THE INTERSECTION, P_2, WITH THE 0°C LINE IN THE SMALL CHART.
3. WITH A TRANSPARENT RULER OR STRAIGHT EDGE, JOIN P_2 TO THE PRESSURE, FOUND ON THE EXTREME RIGHT SIDE OF THE CHART, LOCATING THE INTERSECTION, P_3, OF THE RULER WITH THE DIAGONAL OF THE LARGE SQUARE (DISREGARD C SCALE).
4. JOIN P_3 TO THE VALUE OF $\partial q/\partial \phi$, FOUND AT THE EXTREME TOP OF THE CHART, AND READ THE NUMERICAL VALUE OF α FROM THE INTERSECTION, P_4, OF THE RULER WITH THE SCALE AT THE EXTREME BOTTOM OF THE CHART.
5. GIVE THE SAME SIGN AS THAT OF $\partial q/\partial \phi$ AND RECORD.

II. FINDING β: (USE THE SCALES AROUND THE TWO SMALL SQUARES WITHIN THE LARGE SQUARE)

1. WITH A RULER, JOIN T ON THE TOP SCALE OF THE SMALL LEFT HAND SQUARE TO T_d ON THE BOTTOM SCALE OF THAT SQUARE, LOCATING THE INTERSECTION, O_1, WITH THE DIAGONAL.
2. JOIN O_1 TO THE VALUE OF ω ON THE LEFT SIDE OF THE SQUARE, AND LOCATE THE INTERSECTION, O_2, OF THE RULER WITH THE RIGHT SIDE OF THE SQUARE.
3. JOIN O_2 TO THE VALUE OF P ON THE RIGHT SIDE OF THE RIGHT HAND SMALL SQUARE, LOCATING THE INTERSECTION, O_3 WITH THE DIAGONAL OF THAT SQUARE.
4. JOIN O_3 TO THE VALUE OF γ_c ON THE BOTTOM OF THE RIGHT SMALL SQUARE, AND READ THE NUMERICAL VALUE OF β FROM THE INTERSECTION OF THE RULER WITH THE TOP OF THE SQUARE.
5. GIVE β THE SAME SIGN AS γ_c AND RECORD.

III. FINDING C: (USE THE SCALES ON THE LARGE SQUARE).

1. JOIN P ON THE RIGHT SIDE OF THE SQUARE TO $\gamma_d - \gamma = \Gamma - \gamma$ ON THE LEFT SIDE OF THE SQUARE AND READ THE NUMERICAL VALUE OF C FROM THE INTERSECTION OF THE RULER WITH THE DIAGONAL.
2. GIVE C THE SAME SIGN AS $\Gamma - \gamma$ AND RECORD.

IV. FINDING Σ:

1. Σ IS GIVEN BY THE FORMULA $\alpha + \beta + C = \Sigma$

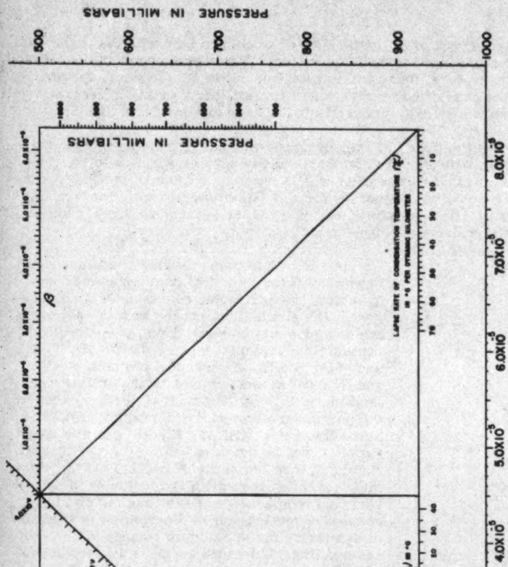


Fig. 5--Divergence nomogram for the solution of equation (6)

For subsequent discussion equation (5) will be written simply as

$$\zeta = \alpha + \beta + \epsilon \quad \ldots\ldots (6)$$

where ζ is proportional to the area a.

As it will be observed later the term β of (6) is very small in comparison with the terms α and ϵ. Consequently, the equation expresses the well-known fact: For a given point in the atmosphere and a given lapse-rate of temperature, there exists a certain - $\delta w/\delta\phi$ for which larger negative values are impossible in the case of convective stability; and there exists a certain - $\delta w/\delta\phi$ for which smaller negative values are impossible in the case of convective instability.

For the element dm, the values at the time t of the observed variables P, T, and w and the derived variables T_s, γ, γ_c, and $\delta w/\delta\phi$ are easily obtainable in the manner which is to be considered. When these values are obtained, the evaluation of ζ is made by the use of the Divergence Nomogram, Figure 5, which is the graphic solution of (6) for ζ. ζ is proportional to the variable a. The relative time rate of change of ζ is a measure, called μ, of the horizontal divergence or convergence which the element is experiencing at that time.

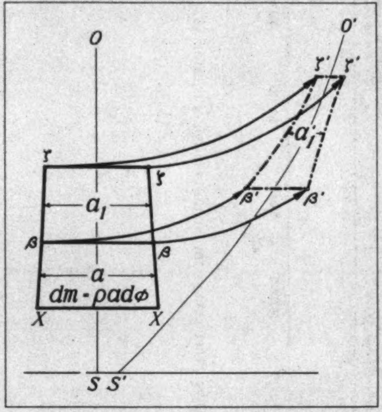


Fig. 6--Soundings in the vertical versus soundings in curved axis of symmetry

In addition to being displaced upward or downward from its initial position as a consequence of the horizontal convergence or divergence, the element dm moves with the horizontal atmospheric circulation. Thus, in order to evaluate the variables γ, γ_c, $\delta w/\delta\phi$, P, T, T_s, and w the position in space of two points X″ and X′ must be determined as the initial and terminal points of the actual trajectory taken by the particular element dm during the time t. Since the curve XBDEF, Figure 4, is the sounding observed at the time t along the vertical SO, Figure 6; then the curve X′B′D′E′F′ (Fig. 4) must establish the spatial variation of the pressure and temperature at the time t + dt along some non-vertical curve S′O′, which is the axis of symmetry for the column composed for the several dm_i. Inasmuch as there usually exists variation in space of the horizontal wind field, the axis of the column is non-vertical and curved. The curve X′B′D′E′F′ therefore is not a directly observable sounding of the atmosphere but is a "synthetic" sounding at the time t + dt of the column of air elements which at the time t was vertical and was located at a particular geographical point P. (The term "synthetic" sounding is due to James E. Miller, "Computation of Vertical Motion from Constant Pressure Charts," which is the third paper in the series, "On Vertical Motion in the Atmosphere," by the Department of Meteorology, New York University.) Likewise, it is possible to suppose that at the time t - dt there is another synthetic sounding X″B″D″E″F″ (not shown in any of the figures) of the column of elements dm_i. Then X″ and X′ are determined as the intersections of each of the two synthetic soundings with that dry adiabat and/or moist adiabat of the pressure-height chart for which X″ is as far below X as X′ is above. Consequently it is necessary to determine the synthetic soundings in order to locate X″ and X′. A method for constructing the synthetic soundings from the observed soundings is shown in the analysis presented in the next section.

As a result of the horizontal convergence or divergence which each element experiences during the time from t - dt to t + dt, all elements dm_i of the column arrive at the same geographical point P at the time t and at their respective levels X, B, D, E, and F. Thus, the fractional rate of change of ζ for any point P during the time from t - dt to t + dt is a measure of the horizontal divergence or convergence at the level X and the geographical point P and the time t.

$$\mu = Kda/2adt \quad \text{(units: sec}^{-1}\text{)} \ldots\ldots (7)$$

An analysis for horizontal convergence and divergence--The practical application of the foregoing considerations will be illustrated by the preparation of an analysis for horizontal convergence and divergence.

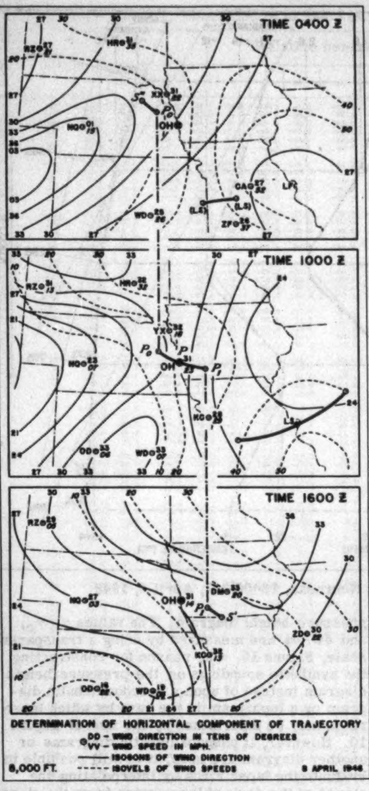


Fig. 7--Determination of horizontal component of trajectory

Since radiosonde observations usually are made at $04^{h}00^{m}$ Z and $16^{h}00^{m}$ Z the time t is $10^{h}00^{m}$ Z and $22^{h}00^{m}$ Z, and the period 2dt is 12 hr. Thus the value μ is the mean horizontal divergence or convergence during the 12-hour period and is identified with the time $10^{h}00^{m}$ Z or $22^{h}00^{m}$ Z.

The following analysis is made for $10^{h}00^{m}$ Z, April 8, 1946.

In order ultimately to evaluate the horizontal convergence and divergence at some point P, the first step is the determination of the horizontal component of a particular air trajectory which arrives at the vertical through P and its horizontal level at the middle of its period. For example, in Figure 7, the S'' and S' are roughly the initial and terminal points of the horizontal component at 8000 ft for the particular 12-hour trajectory of the element which arrives at 8000 ft over Omaha at $10^{h}00^{m}$ Z. In the same way the initial and terminal points of the trajectories passing through Omaha may be located on other constant levels.

Next, the values of pressure, temperature, and mixing ratio at the initial and terminal points of each trajectory are determined by interpolation between the isobars, isotherms, and mixing ratio lines on the corresponding constant level charts. The values for the initial points of the trajectories are points on the sounding X''B'' D''E''F''. In the same way, the sounding X'B' D'E'F' can be constructed from the data of the terminal points [see "References" at end of paper, MILLER]. For example, the terminal point S', Figure 7, is located on the 8000-foot chart, Figure 8. The values of pressure, temperature, relative humidity, and mixing ratio for S' are interpolated from that chart and are plotted as the points which are shown directly to the right in Figure 8. The condensation temperature curves are plotted by using Table 1 (published by the Zentralen Wetterdienstgruppe, 1943).

As it is observed later the value for γ_c can be more easily obtained from the condensation temperature curves constructed in this manner than from the characteristic curves, which ordinarily are used for representing condensation temperatures. The values of these variables for the terminal points on the other constant level charts are also located on the pressure-height diagram for constructing the $16^{h}00^{m}$ Z synthetic sounding for Omaha.

The third step is the determination of the actual trajectory of the element dm. In Figure 9 the $04^{h}00^{m}$ Z and $16^{h}00^{m}$ Z synthetic soundings for Omaha are shown. The continuous curves are plotted from the data that have been interpolated at the initial points of a set of trajectories on the $04^{h}00^{m}$ Z charts for the five levels; whereas, the dotted-dashed curves are plotted from the terminal points of the same set of trajectories on the $16^{h}00^{m}$ Z charts. The image point of the element in the pressure-height diagram moves along a dry adiabat from point X'' on sounding S'' to point X' on sounding S'. The point X'' is as far above the 10,000-foot level at $04^{h}00^{m}$ Z as X' is below that level at $16^{h}00^{m}$ Z.

The fourth step is the determination of the values at X'' and X' in Figure 9 for P, T, w, T_s, γ, γ_c, and $\delta w/\delta\phi$. The values P, T, w, and T_s can be read directly from the coordinates of the

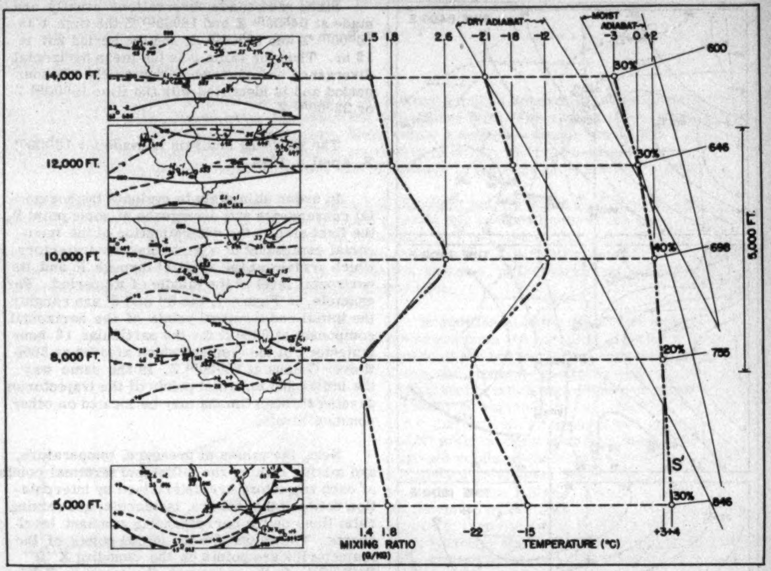


Fig. 8--Synthetic sounding for Omaha, Nebraska, 16^h00^m Z, April 8, 1946

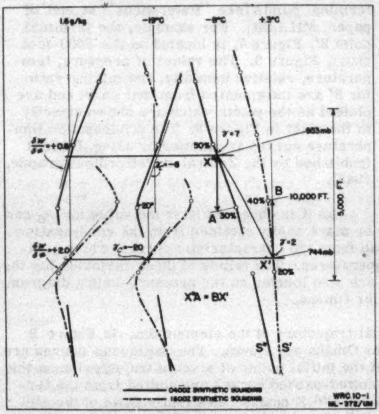

1.6g/kg
-19°C
-8°C
+3°C
$\frac{\delta w}{\delta \phi}=+0.6$
$\gamma=7$
603mb
50%
X
$\gamma_c=6$
B
10,000 FT.
40%
A
30%
5,000 FT.
20°
$\frac{\delta w}{\delta \phi}=+2.0$
$\gamma_c=20$
$\gamma=2$
744mb
X'
20%
X'A = BX'
S"
S'
0400Z SYNTHETIC SOUNDING
1600Z SYNTHETIC SOUNDING
WRC 10-1
ML-372/UM

Fig. 9--Determination of initial and terminal points of actual trajectory for 12-hour period, with mean position at 10,000-foot level and at Omaha, April 8, 1946

pressure-height diagram. The values γ, γ_C, and $\delta w/\delta \phi$ are measured by using a transparent scale, Figure 10. One reason for constructing the synthetic soundings on the pressure-height diagram instead of upon a pseudoadiabatic diagram or a tephigram is the ease by which lapse rates may be determined by the use of Figure 10. However, if pseudoadiabatic diagrams or another diagram are used, it is still possible to evaluate the lapse rates by interpolating the slopes of the desired lapse rates from the slopes of the moist adiabats and dry adiabats printed in the diagram. The value of the moist adiabatic lapse rate at any point can be obtained by using Figure 11. The values for these variables are shown in a portion of a tabulation form, Table 2.

The fifth step is the determination of the values for ζ for 04^h00^m Z and 16^h00^m Z. The values are entered into the Divergence Nomogram, Figure 5, according to the directions on the Nomogram.

Finally, the last step is the evaluation of μ. This value at 10,000 ft for Omaha is + 0.451/six hr, which may be interpreted as meaning that at 10,000 ft over Omaha, two particles of air one mi apart are going away from each other at the rate of 0.226 mi/six hr.

Table 1--Condensation temperatures in degrees C in terms of temperature and relative humidity

Temp. in °C	Relative humidity in per cent																	Temp. in °C
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	
-40	-57.4	-55.5	-53.5	-51.8	-50.2	-49.1	-47.9	-46.8	-45.7	-44.9	-43.9	-43.1	-42.4	-41.7	-41.1	-40.5	-40.0	-40
-39	-56.5	-54.5	-52.5	-50.8	-49.3	-48.1	-46.9	-45.8	-44.8	-43.8	-43.0	-42.2	-41.5	-40.7	-40.1	-39.5	-39.0	-39
-38	-55.6	-53.6	-51.6	-49.9	-48.4	-47.2	-46.0	-44.9	-43.8	-42.9	-42.0	-41.2	-40.5	-39.8	-39.2	-38.6	-38.0	-38
-37	-54.8	-52.6	-50.6	-48.9	-47.4	-46.3	-45.0	-43.9	-42.9	-42.0	-41.1	-40.3	-39.6	-38.8	-38.2	-37.6	-37.0	-37
-36	-53.9	-51.7	-49.7	-48.0	-46.4	-45.2	-44.1	-43.0	-41.9	-41.0	-40.2	-39.4	-38.6	-37.9	-37.3	-36.6	-36.0	-36
-35	-53.0	-50.7	-48.7	-47.0	-45.4	-44.2	-43.1	-42.0	-41.0	-40.1	-39.2	-38.4	-37.7	-36.9	-36.3	-35.6	-35.0	-35
-34	-52.1	-49.8	-47.8	-46.0	-44.5	-43.3	-42.1	-41.0	-40.1	-39.2	-38.3	-37.5	-36.8	-36.0	-35.3	-34.7	-34.0	-34
-33	-51.2	-48.8	-46.8	-45.1	-43.5	-42.3	-41.2	-40.1	-39.1	-38.2	-37.4	-36.6	-35.8	-35.0	-34.4	-33.7	-33.0	-33
-32	-50.4	-47.9	-45.9	-44.1	-42.5	-41.3	-40.2	-39.1	-38.2	-37.3	-36.5	-35.7	-34.9	-34.1	-33.4	-32.7	-32.0	-32
-31	-49.5	-46.9	-44.9	-43.2	-41.6	-40.4	-39.3	-38.2	-37.2	-36.3	-35.5	-34.7	-33.9	-33.1	-32.5	-31.8	-31.0	-31
-30	-48.6	-46.0	-44.0	-42.2	-40.6	-39.4	-38.3	-37.2	-36.2	-35.4	-34.6	-33.8	-33.0	-32.2	-31.5	-30.8	-30.0	-30
-29	-47.7	-45.2	-43.2	-41.4	-39.8	-38.5	-37.4	-36.3	-35.4	-34.4	-33.6	-32.8	-32.0	-31.2	-30.5	-29.8	-29.0	-29
-28	-46.9	-44.3	-42.3	-40.5	-38.9	-37.7	-36.5	-35.4	-34.4	-33.5	-32.7	-31.8	-31.0	-30.2	-29.5	-28.8	-28.0	-28
-27	-46.0	-43.5	-41.5	-39.7	-38.1	-36.8	-35.6	-34.5	-33.5	-32.5	-31.7	-30.9	-30.0	-29.2	-28.5	-27.8	-27.0	-27
-26	-45.2	-42.7	-40.6	-38.8	-37.3	-35.9	-34.7	-33.6	-32.6	-31.6	-30.7	-29.9	-29.0	-28.2	-27.5	-26.8	-26.0	-26
-25	-44.3	-41.8	-39.8	-38.0	-36.4	-35.0	-33.8	-32.6	-31.6	-30.6	-29.7	-28.9	-28.0	-27.3	-26.4	-25.7	-25.0	-25
-24	-43.4	-41.0	-39.0	-37.2	-35.6	-34.2	-33.0	-31.7	-30.7	-29.7	-28.8	-27.9	-27.0	-26.3	-25.4	-24.7	-24.0	-24
-23	-42.5	-40.2	-38.1	-36.3	-34.8	-33.3	-32.1	-30.8	-29.8	-28.7	-27.8	-26.9	-26.0	-25.2	-24.4	-23.7	-23.0	-23
-22	-41.7	-39.4	-37.3	-35.5	-34.0	-32.4	-31.2	-29.9	-28.9	-27.8	-26.8	-26.0	-25.0	-24.2	-23.4	-22.7	-22.0	-22
-21	-40.9	-38.5	-36.4	-34.6	-33.1	-31.6	-30.3	-29.0	-27.9	-26.8	-25.9	-25.0	-24.0	-23.2	-22.4	-21.7	-21.0	-21
-20	-40.0	-37.7	-35.6	-33.8	-32.3	-30.7	-29.4	-28.1	-27.0	-25.9	-24.9	-24.0	-23.0	-22.2	-21.4	-20.7	-20.0	-20
-19	-39.2	-36.9	-34.7	-32.9	-31.4	-29.8	-28.4	-27.1	-26.0	-24.9	-23.9	-23.0	-22.0	-21.2	-20.4	-19.7	-19.0	-19
-18	-38.5	-36.0	-33.9	-32.0	-30.4	-28.8	-27.5	-26.2	-25.1	-23.9	-22.9	-22.0	-21.0	-20.2	-19.4	-18.7	-18.0	-18
-17	-37.7	-35.2	-33.0	-31.1	-29.5	-27.9	-26.5	-25,2	-24.1	-23.0	-22.0	-21.0	-20.0	-19.2	-18.4	-17.7	-17.0	-17
-16	-36.9	-34.4	-32.2	-30.2	-28.6	-27.0	-25.6	-24.3	-23.1	-22.0	-21.0	-20.0	-19.0	-18.2	-17.4	-16.7	-16.0	-16
-15	-36.1	-33.5	-31.3	-29.3	-27.6	-26.0	-24.6	-23.3	-22.1	-21.0	-20.0	-19.0	-18.0	-17.2	-16.4	-15.7	-15.0	-15
-14	-35.4	-32.7	-30.4	-28.5	-26.7	-25.1	-23.7	-22.3	-21.2	-20.0	-19.0	-18.1	-17.1	-16.2	-15.4	-14.7	-14.0	-14
-13	-34.6	-31.9	-29.6	-27.6	-25.8	-24.2	-22.7	-21.4	-20.2	-19.0	-18.0	-17.1	-16.1	-15.2	-14.4	-13.7	-13.0	-13
-12	-33.8	-31.1	-28.7	-26.7	-24.9	-23.3	-21.8	-20.4	-19.2	-18.1	-17,1	-16.1	-15.1	-14.2	-13.4	-12.7	-12.0	-12
-11	-33.1	-30.2	-27.9	-25.8	-23.9	-22.3	-20.8	-19.5	-18.3	-17.1	-16.1	-15.1	-14.1	-13.2	-12.4	-11.7	-11.0	-11
-10	-32.3	-29.4	-27.0	-24.9	-23.0	-21.4	-19.9	-18.5	-17.3	-16.1	-15.1	-14.1	-13.1	-12.2	-11.4	-10.7	-10.0	-10
- 9	-31.4	-28.5	-26.1	-23.9	-22.1	-20.4	-18.9	-17.5	-16.3	-15.2	-14.1	-13.1	-12.2	-11.3	-10.5	- 9.7	- 9.0	- 9
- 8	-30.5	-27.6	-25.1	-23.0	-21.1	-19.5	-18.0	-16.6	-15.3	-14.2	-13.2	-12.2	-11.2	-10.3	- 9.5	- 8.8	- 8.0	- 8
- 7	-29.6	-26.6	-24.2	-22.0	-20.1	-18.5	-17.0	-15.6	-14.4	-13.3	-12.2	-11.2	-10.3	- 9.4	- 8.6	- 7.8	- 7.0	- 7
- 6	-28.7	-25.7	-23.2	-21.1	-19.2	-17.6	-16.1	-14.7	-13.4	-12.3	-11.3	-10.3	- 9.3	- 8.4	- 7.6	- 6.9	- 6.0	- 6
- 5	-27.8	-24.8	-22.3	-20.1	-18.2	-16.6	-15.1	-13.7	-12.4	-11.4	-10.3	- 9.3	- 8.4	- 7.5	- 6.7	- 5.9	- 5.0	- 5
- 4	-27.0	-24.0	-21.5	-19.3	-17.4	-15.8	-14.3	-12.8	-11.5	-10.5	- 9.4	- 8.4	- 7.5	- 6.6	- 5.7	- 4.9	- 4.0	- 4
- 3	-26.2	-23.2	-20.7	-18.5	-16.6	-14.9	-13.4	-12.0	-10.7	- 9.6	- 8.5	- 7.5	- 6.6	- 5.6	- 4.7	- 3.9	- 3.0	- 3
- 2	-25.3	-22.4	-19.9	-17.6	-15.7	-14.1	-12.6	-11.1	- 9.8	- 8.7	- 7.6	- 6.7	- 5.6	- 4.7	- 3.8	- 2.9	- 2.0	- 2
- 1	-24.5	-21.6	-19.1	-16.8	-14.9	-13.2	-11.7	-10.3	- 9.0	- 7.8	- 6.7	- 5.8	- 4.7	- 3.7	- 2.8	- 1.9	- 1.0	- 1
0	-23.4	-20.8	-18.2	-16.0	-14.1	-12.4	-10.9	- 9.4	- 8.1	- 6.9	- 5.8	- 4.9	- 3.8	- 2.8	- 1.8	- 0.9	0.0	0
+ 1	-23.0	-20.0	-17.4	-15.2	-13.2	-11.5	-10.0	- 8.5	- 7.2	- 6.0	- 4.9	- 3.9	- 2.8	- 1.8	- 0.8	+ 0.1	+ 1.0	+ 1
+ 2	-22.2	-19.2	-16.6	-14.3	-12.4	-10.7	- 9.2	- 7.7	- 6.4	- 5.0	- 4.0	- 2.9	- 1.8	- 0.8	+ 0.2	+ 1.1	+ 2.0	+ 2
+ 3	-21.5	-18.3	-15.7	-13.5	-11.5	- 9.8	- 8.3	- 6.8	- 5.5	- 4.1	- 3.0	- 2.0	- 0.8	+ 0.1	+ 1.1	+ 2.0	+ 3.0	+ 3
+ 4	-20.7	-17.5	-14.9	-12.6	-10.7	- 9.0	- 7.5	- 6.0	- 4.7	- 3.1	- 2.1	- 1.0	- 0.2	+ 1.1	+ 2.1	+ 3.0	+ 4.0	+ 4
+ 5	-20.0	-16.7	-14.0	-11.8	- 9.8	- 8.1	- 6.6	- 5.1	- 3.8	- 2.2	- 1,2	0.0	+ 1.2	+ 2.1	+ 3.1	+ 4.0	+ 5.0	+ 5
+ 6	-19.1	-15.9	-13.3	-11.0	- 9.0	- 7.2	- 5.7	- 4.2	- 2.8	- 1.3	- 0.2	+ 1.0	+ 2.2	+ 3.1	+ 4.1	+ 5.0	+ 6.0	+ 6
+ 7	-18.3	-15.1	-12.4	-10.2	- 8.1	- 6.4	- 4.8	- 3.2	- 1.8	- 0.3	+ 0.8	+ 2.0	+ 3.2	+ 4.1	+ 5.1	+ 6.0	+ 7.0	+ 7
+ 8	-17.4	-14.3	-11.7	- 9.3	- 7.3	- 5.5	- 3.8	- 2.3	- 0.9	+ 0.6	+ 1.7	+ 3.0	+ 4.1	+ 5.1	+ 6.1	+ 7.1	+ 8.0	+ 8
+ 9	-16.6	-13.5	-10.9	- 8.5	- 6.4	- 4.7	- 2.9	- 1.3	+ 0.1	+ 1.6	+ 2.7	+ 4.0	+ 5.1	+ 6.1	+ 7.1	+ 8.1	+ 9.0	+ 9
+10	-15.7	-12.7	-10.1	- 7.7	- 5.6	- 3.8	- 2.0	- 0.4	+ 1.1	+ 2.5	+ 3.7	+ 5.0	+ 6.1	+ 7.1	+ 8.1	+ 9.1	+10.0	+10
+11	-14.9	-11.9	- 9.2	- 6.8	- 4.7	- 2.9	- 1.1	+ 0.6	+ 2.1	+ 3.5	+ 4.7	+ 5.9	+ 7.0	+ 8.1	+ 9.1	+10.1	+11.0	+11
+12	-14.1	-11.0	- 8.4	- 6.0	- 3.8	- 2.0	- 0.1	+ 1.6	+ 3.0	+ 4.5	+ 5.6	+ 6.8	+ 8.0	+ 9.0	+10.1	+11.1	+12.0	+12
+13	-13.3	-10.2	- 7.5	- 5.1	- 3.0	- 1.0	+ 0.8	+ 2.6	+ 4.0	+ 5.5	+ 6.6	+ 7.8	+ 8.9	+10.0	+11.0	+12.0	+13.0	+13
+14	-12.5	- 9.3	- 6.7	- 4.3	- 2.1	- 0.1	+ 1.8	+ 3.6	+ 4.9	+ 6.5	+ 7.6	+ 8.7	+ 9.9	+10.9	+12.0	+13.0	+14.0	+14
+15	-11.7	- 8.5	- 5.8	- 3.4	- 1.2	+ 0.8	+ 2.7	+ 4.6	+ 5.9	+ 7.5	+ 8.5	+ 9.6	+10.8	+11.9	+13.0	+14.0	+15.0	+15
+16	-11.0	- 7.8	- 5.0	- 2.6	- 0.3	+ 1.7	+ 3.6	+ 5.4	+ 6.7	+ 8.4	+ 9.4	+10.5	+11.7	+12.9	+14.0	+15.0	+16.0	+16
+17	-10.3	- 7.0	- 4.3	- 1.8	+ 0.5	+ 2.5	+ 4.4	+ 6.3	+ 7.6	+ 9.2	+10.3	+11.4	+12.7	+13.8	+14.9	+16.0	+17.0	+17
+18	- 9.7	- 6.2	- 3.5	- 0.9	+ 1.4	+ 3.4	+ 5.3	+ 7.0	+ 8.4	+10.1	+11.1	+12.4	+13.6	+14.8	+15.9	+16.9	+18.0	+18
+19	- 9.0	- 5.5	- 2.8	- 0.1	+ 2.2	+ 4.3	+ 6.1	+ 7.8	+ 9.3	+10.9	+12.0	+13.3	+14.6	+15.7	+16.8	+17.9	+19.0	+19
+20	- 8.3	- 4.8	- 2.0	+ 0.7	+ 3.1	+ 5.1	+ 7.0	+ 8.6	+10.1	+11.8	+12.9	+14.2	+15.5	+16.7	+17.8	+18.9	+20.0	+20
+21	- 7.6	- 4.1	- 1.2	+ 1.5	+ 3.9	+ 5.9	+ 7.8	+ 9.5	+11.0	+12.7	+13.8	+15.2	+16.5	+17.7	+18.8	+19.9	+21.0	+21
+22	- 6.8	- 3.4	- 0.4	+ 2.3	+ 4.7	+ 6.6	+ 8.7	+10.4	+11.9	+13.5	+14.8	+16.1	+17.4	+18.7	+19.8	+20.9	+22.0	+22
+23	- 6.1	- 2.6	+ 0.3	+ 3.1	+ 5.6	+ 7.6	+ 9.5	+11.2	+12.8	+14.4	+15.7	+17.1	+18.4	+19.6	+20.8	+21.9	+23.0	+23
+24	- 5.3	- 1.9	+ 1.1	+ 3.8	+ 6.4	+ 8.5	+10.4	+12.1	+13.7	+15.2	+16.7	+18.0	+19.3	+20.6	+21.8	+22.9	+24.0	+24
+25	- 4.6	- 1.2	+ 1.9	+ 4.6	+ 7.2	+ 9.3	+11.2	+13.0	+14.6	+16.1	+17.6	+19 0	+20.3	+21.6	+22.8	+23.9	+25.0	+25
+26	- 3.8	- 0.3	+ 2.7	+ 5.5	+ 8.0	+10.1	+12.1	+13.9	+15.5	+17.1	+18.6	+20.0	+21.3	+22.6	+23.8	+24.9	+26.0	+26
+27	- 3.0	+ 0.6	+ 3.6	+ 6.3	+ 8.9	+11.0	+13.0	+14.8	+16,5	+18.1	+19.6	+21.0	+22.3	+23.6	+24.8	+25.9	+27.0	+27
+28	- 2.3	+ 1.4	+ 4.4	+ 7.2	+ 9.7	+11.8	+13.8	+15.7	+17.4	+19.1	+20.5	+22.0	+23.3	+24.6	+25.9	+27.0	+28.0	+28
+29	- 1.4	+ 2.3	+ 5.3	+ 8.0	+10.6	+12.7	+14.7	+16.6	+18.4	+20.0	+21.5	+23.0	+24.3	+25.6	+26.9	+28.0	+29.0	+29
+30	- 0.6	+ 3.2	+ 6.1	+ 8.9	+11.4	+13.6	+15.6	+17.5	+19.3	+21.0	+22.5	+24.0	+25.3	+26.6	+27.9	+29.0	+30.0	+30
+31	+ 0.2	+ 3.9	+ 6.9	+ 9.7	+12.3	+14.4	+16.5	+18.5	+20.3	+22.1	+23.4	+24.9	+26.2	+27.6	+28.8	+30.0	+31.0	+31
+32	+ 1.0	+ 4.6	+ 7.7	+10.5	+13.1	+15.4	+17.6	+19.4	+21.2	+23.1	+24.4	+25.9	+27.3	+28.5	+29.8	+30.9	+32.0	+32
+33	+ 1.7	+ 5.4	+ 8.4	+11.3	+14.0	+16.3	+18.4	+20.4	+22.2	+24.4	+25.3	+26.8	+28.1	+29.6	+30.7	+31.8	+33.0	+33
+34	+ 2.5	+ 6.1	+ 9.2	+12.1	+14.8	+17.3	+19.4	+21.3	+23.1	+25.5	+26.3	+27.8	+29.1	+30.4	+31.7	+32.8	+34.0	+34
+35	+ 3.3	+ 6.8	+10.0	+12.9	+15.7	+18.2	+20.3	+22.3	+24.1	+26.6	+27.3	+28.7	+30.0	+31.4	+32.6	+33.8	+35.0	+35
+36	+ 4.0	+ 7.6	+10.9	+13.8	+16.6	+19.0	+21.2	+23.2	+25.0	+27.3	+28.1	+29.6	+30.9	+32.4	+33.6	+34.8	+36.0	+36
+37	+ 4.8	+ 8.4	+11.7	+14.6	+17.4	+19.9	+22.1	+24.1	+25.9	+28.0	+29.0	+30.5	+31.9	+33.3	+34.6	+35.8	+37.0	+37
+38	+ 5.5	+ 9.3	+12.6	+15.5	+18.3	+20.7	+22.9	+25.0	+26.7	+28.9	+30.0	+31.5	+32.8	+34.3	+35.5	+36.8	+38.0	+38
+39	+ 6.3	+10.1	+13.4	+16.3	+19.1	+21.6	+23.8	+25.9	+27.6	+29.8	+30.9	+32.4	+33.8	+35.2	+36.5	+37.8	+39.0	+39
+40	+ 7.0	+10.9	+14.3	+17.2	+20.0	+22.4	+24.7	+26.8	+28.5	+30.8	+31.8	+33.3	+34.7	+36.2	+37.5	+38.8	+40.0	+40

A few characteristics of the tabulation of values in Table 2 may be observed. The values of α at $04^{h}00^{m}$ Z and $16^{h}00^{m}$ Z for any one station (that is, for a certain element dm) and level are always of the same sign. Likewise, the two values of β are always the same sign. The two values of ϵ are always positive. Consequently, ζ is always of the same sign and the value of μ (six hr)$^{-1}$ is always between the limits ± 1. The magnitude of β is negligible; whereas, both α and ϵ are approximately of the same order of magnitude, although α is usually somewhat smaller.

In Figure 12, the value + 0.451 for Omaha has been plotted, together with values of μ for 44 other geographical points evenly distributed over the area of the United States. The value + 0.451 is also plotted in Figure 13, a vertical section along 42°N latitude.

Figures 13 and 14 may be compared with Figure 12 for interpreting the horizontal convergence and divergence in terms of kinematical and dynamical considerations and the associated weather.

DIRECTIONS

1. PLACE SCALE SO THAT VERTICAL LINES ARE PARALLEL TO ISOTHERMS AND ENCIRCLED POINT LIES ON THE POINT X_1 AT WHICH LAPSE RATE IS TO BE TAKEN.

2. NOTE PRESSURE P AT WHICH THE HORIZONTAL LINE AA' CROSSES THE ISOTHERM THROUGH X_1.

3. FOLLOW DOWN THE ISOBAR P UNTIL IT INTERSECTS THE SOUNDING AT X_2 AND READ THE LAPSE RATE FROM THE VERTICAL LINE PASSING THROUGH X_2.*

* IF THE LAPSE RATE CHANGES BETWEEN X_1 AND X_2, USE THE LINE BB' INSTEAD OF AA' AND DOUBLE THE READING. IF THE LAPSE RATE REMAINS CONSTANT FOR A SUFFICIENT DISTANCE, FOR GREATER ACCURACY USE THE LINE CC' INSTEAD OF AA' AND HALVE THE READING.

NOTE: THE ABOVE RULES APPLY TO γ AND γ_c. FOR $-\delta w/\delta\phi$, PROCEED AS ABOVE BUT TAKE ONE-TENTH OF THE LABELED VALUE.

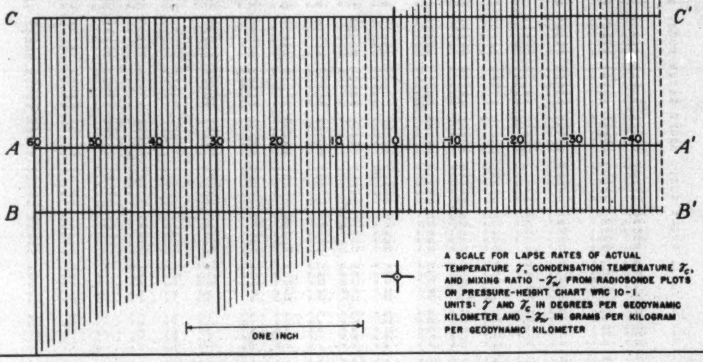
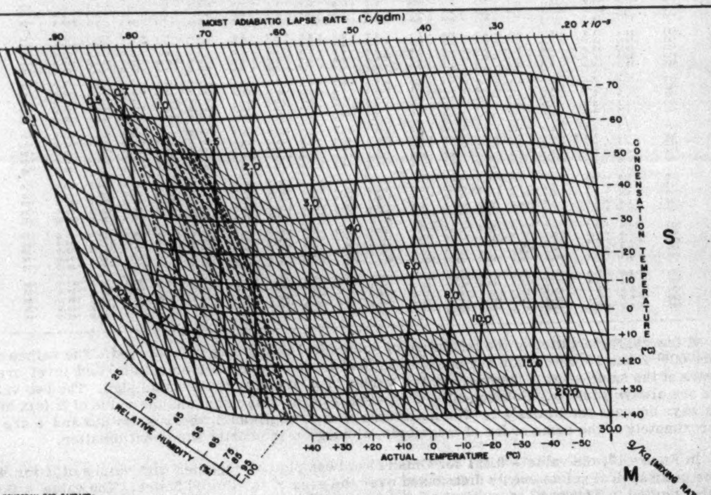

C
C'
A
A'
B
B'
60
50
40
30
20
10
0
-10
-20
-30
-40
ONE INCH
A SCALE FOR LAPSE RATES OF ACTUAL TEMPERATURE γ, CONDENSATION TEMPERATURE γ_c, AND MIXING RATIO $-\gamma_w$ FROM RADIOSONDE PLOTS ON PRESSURE-HEIGHT CHART WRC 10-1.
UNITS: γ AND γ_c IN DEGREES PER GEODYNAMIC KILOMETER AND $-\gamma_w$ IN GRAMS PER KILOGRAM PER GEODYNAMIC KILOMETER

Fig. 10--Scale for lapse rates of actual temperature γ, condensation temperature γ_C, and mixing ratio $\delta w/\delta\phi$ from radiosonde plots on pressure-height chart WRC 10-1. Units: γ and γ_C in °C/geodynamic km and $\delta w/\delta\phi$ in g/kg/geodynamic km



NOMOGRAM FOR FINDING:

A. CONDENSATION TEMPERATURE IN TERMS OF:
  1. ACTUAL TEMPERATURE
  2. RELATIVE HUMIDITY

B. LAPSE RATE OF TEMPERATURE ALONG A SATURATION-ADIABATIC PROCESS AT:
  1. ANY POINT IN TERMS OF:
    a. ACTUAL TEMPERATURE (CONDENSATION TEMPERATURE ON SCALE S)
    b. MAXIMUM MIXING RATIO (ACTUAL MIXING RATIO ON SCALE M)
  2. CHARACTERISTIC CONDENSATION POINT IN TERMS OF:
    a. ACTUAL TEMPERATURE,
    b. ACTUAL MIXING RATIO, AND
    c. RELATIVE HUMIDITY - ALL AT ANY POINT ALONG AN UNSATURATION-ADIABATIC PROCESS ENDING AT THE CHARACTERISTIC POINT.

Fig. 11--Diagram for determining moist adiabatic lapse rate at any point

Table 2--The values of X″ and X′ in Figure 9 for p in mb, T in °C, w in g/kg, T_s in °C, γ and γ_c in °C/geodynamic km, and $\delta w/\delta\phi$ in g/kg/geodynamic km; and the determination of the horizontal divergence, $\mu = i/\lambda$ at 10,000 ft over Omaha (Sta. 553) for 12-hour period from 04^h00^m to 16^h00^m Z, April 8, 1946

POINT *	04Z	16Z
γ	7	2
$10-\gamma$	3	8
γ_c	-8	-20
$\delta w/\delta\phi$	+0.6	+2.0
P	653	744
T	-8	+3
R	45	25
w	1.6	1.6
T_s	-19	-20
$\alpha \times 10^{+5}$	+0.20	+0.74
$\beta \times 10^{+5}$	-.02	-.09
$\epsilon \times 10^{+5}$	+.47	+1.07
$\zeta : \alpha+\beta+\epsilon$	+.65	+1.72
η	+1.72	
$i : \zeta-\eta$	-1.07	= +.451
$\lambda : \zeta+\eta$	+2.37	

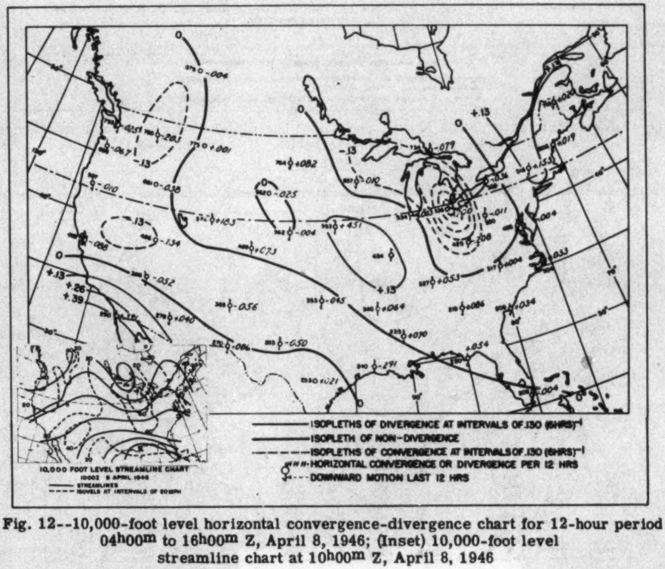

+.13
+.26
+.39
-.13
+.451
-.079
+.13
-.050
-.291
+.054
+.004
10,000 FOOT LEVEL STREAMLINE CHART
1000Z 8 APRIL 1946
STREAMLINES
ISOVELS AT INTERVALS OF 20MPH
ISOPLETHS OF DIVERGENCE AT INTERVALS OF .130 (6HRS)⁻¹
ISOPLETH OF NON-DIVERGENCE
ISOPLETHS OF CONVERGENCE AT INTERVALS OF .130 (6HRS)⁻¹
HORIZONTAL CONVERGENCE OR DIVERGENCE PER 12 HRS
DOWNWARD MOTION LAST 12 HRS

Fig. 12--10,000-foot level horizontal convergence-divergence chart for 12-hour period 04^h00^m to 16^h00^m Z, April 8, 1946; (Inset) 10,000-foot level streamline chart at 10^h00^m Z, April 8, 1946

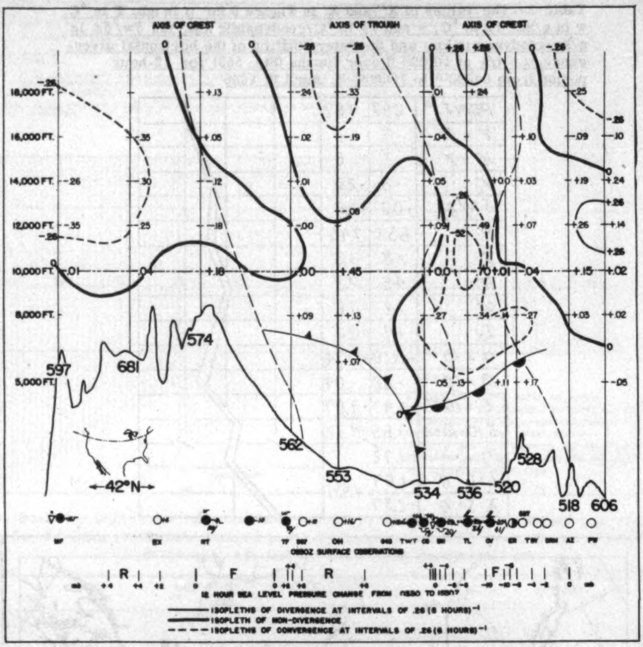
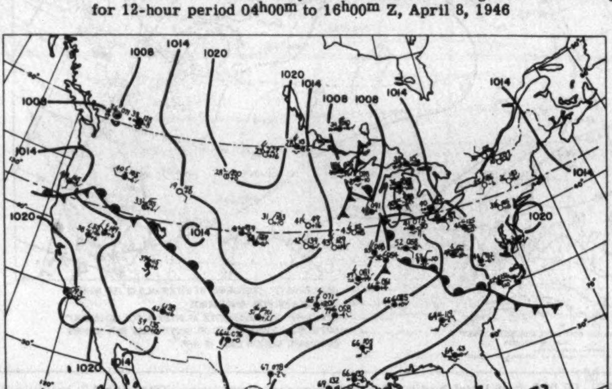


Fig. 13--Vertical section at 42°N with analysis of horizontal divergence and convergence for 12-hour period $04^{h}00^{m}$ to $16^{h}00^{m}$ Z, April 8, 1946


1008
1014
1020
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1008
1008
1014

Fig. 14--Surface chart, $09^{h}30^{m}$ Z, April 8, 1946

Summary

In routine practice, the foregoing procedure has been considerably simplified. The standard constant pressure charts are used instead of the constant level charts, which here have been prepared at more frequent levels, by assuming that the wind observations currently referred to constant level are also observed winds for the corresponding constant pressure surfaces. The term β is not evaluated; therefore, only the variables T, P, R, γ, and $\delta w/\delta\phi$ are obtained for getting μ. Wherever the large-scale motion of the atmosphere is small, the column composed of the several elements dm_i is usually vertical and remains near the point of observation, especially if the radiosonde observations are made at intervals of six hr. Consequently, it is not necessary to construct the synthetic soundings. Instead, the points X'' and X' are determined from successive and observed soundings.

In some respects, the evaluation of horizontal convergence and divergence in this manner does not appear to be practicable. The amount of effort required is considerable. It is doubtful whether other than the forecast centers with adequate personnel could accomplish this form of analysis in daily practice. Accurate analysis for moisture is a stringent requirement for reliable evaluation of horizontal convergence and divergence by this method. Since present-day observations of relative humidity are rather inaccurate, it is questionable whether this method can be successfully applied.

APPENDIX I

The spatial variation of potential temperature is obtained from Poisson's equation, which for dry air is:

$$\theta = T(100/P)^{R/c_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where R = specific gas constant for dry air and c_p = specific heat at constant pressure of dry air.

$$(1/\theta)(\delta\theta/\delta\phi) = (1/T)[\,\delta T/\delta\phi \; - \; (\alpha/c_p)(\delta P/\,\delta\phi)]$$

where α is specific volume of dry air.

$$(1/\theta)(\,\delta\theta/\delta\phi) = (1/T)(\gamma_d - \gamma) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where $\gamma_d = 1/c_p$ dry adiabatic lapse rate of temperature.

Poisson's equation for moist air is

$$\theta = T(100/P)^{R^*/c_p{}^*} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where

$$R^*/c_p{}^* \fallingdotseq (R/c_p)(1 - 0.333w)$$

The second factor amounts to a percentage variation to R/c_p of one per cent for the case of maximum water vapor pressure. Consequently, equation (2) is approximately valid for moist air.

The spatial variation of equivalent potential temperature is obtained by differentiation of Rossby's equation written in the form

$$\theta_e = \theta(1 + 0.46w)e^{(Lw/c_pT_s)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

$$\begin{aligned}\delta\theta_e/\,\theta_e\,\delta\phi = \;& \delta\theta/\theta\,\delta\phi + [0.46/(1 + 0.46w)]\,\delta w/\delta\phi + (L/c_pT_s)\,\delta w/\delta\phi \\ & + (w/c_pT_s)\,\delta L/\delta\phi - (Lw/c_pT_s{}^2)\,\delta T_s/\delta\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)\end{aligned}$$

HOLMBOE, FORSYTHE, and GUSTIN [1945, p. 48] give an equation for L, in meter-ton-second units, as follows:

$$L = (2.500 - 0.002274t^\circ C) \times 10^6 \text{ kilojoules per ton,}$$

which, on differentiation, yields: $\delta L/\delta T = \delta L/\delta(t^\circ C) = -\,2.27 \times 10^3$. Writing $\delta L/\delta\phi = (\delta L/\delta T)(\delta T/\delta\phi) = 2.27 \times 10^3\gamma$, substituting in the fourth term on the right hand side of (12), and replacing the first term on the right hand side from equation (9):

$$\delta\theta_e/\theta_e\delta\phi = (1/T)(\gamma_d - \gamma) + [0.46/(1 + 0.46w) + L/c_pT_s]\delta w/\delta\phi + 2.27 \times 10^3 w\gamma/c_pT_s + Lw\gamma_c/c_pT_s^2 \quad \ldots\ldots\ldots\ldots (13)$$

where $\gamma_c = -\delta T_s/\delta\phi$.

In order to compare the magnitudes of the terms in (13), each term has been evaluated for four particular conditions of the atmosphere. The magnitudes of the terms in Table 3 have been obtained by using the values of the quantities in Table 4. Assuming, for the first comparison in Table 3, the most extreme conditions of a dry-adiabatic atmosphere with a maximum water-vapor content, the third term has its maximum value; whereas, the other terms are zero. In the second comparison, the values which are given to pressure, temperature, and moisture are representative of the conditions in which the evaluation of horizontal convergence is usually made. But the values for the lapse rates of actual temperature, condensation temperature, and mixing ratio have been determined by the requirement that the terms in equation (13) be equal to each other. Under these circumstances the atmosphere has a temperature lapse rate which is but 0.5 per cent less than a dry-adiabatic lapse rate, and moisture lapse rates which are essentially those of a completely mixed atmosphere. The third and fourth comparisons are based on the data in Table 2, and they consequently provide a comparison among the terms for two typical conditions of the atmosphere. It appears from Tables 3 and 4 that the third term of equation (13) is very small compared with the other terms. Therefore, neglecting the third term, we obtain

$$\delta\theta_e/\theta_e\delta\phi = 0.46/(1 + 0.46w)\delta w/\delta\phi + (L/c_pT_s)\delta w/\delta\phi + Lw\gamma_c/c_pT_s^2 + (1/T)(\gamma_d - \gamma) \ldots \quad (2)$$

Table 3--A comparison of the magnitudes of the terms in equation (13)

Term	Value of the terms (× 10⁻⁹) for four different conditions of the atmosphere			
	Comparison 1	Comparison 2	Comparison 3	Comparison 4
$(1/T)(\gamma_d - \gamma)$	0	17	1100	2900
$[0.46/(1 + 0.46w) + L/c_pT_s]\delta w/\delta\phi$	0	17	610	2000
$2.27 \times 10^3 w\gamma/c_pT_s$	200	17	10	3
$Lw\gamma_c/c_pT_s^2$	0	17	49	130

Table 4--Magnitudes of basic quantities used for determining the magnitudes of terms shown in Table 3

Comparison no.	γ	γ_c	$\delta w/\delta\phi$	P	T	w
	°C/dynamic km	°C/dynamic km	g/kg/dynamic km	mb	°C	g/kg
1	10.01	0	0	1000	+ 37	30
2	9.95	2.29	0.026	700	+ 0.6	2.0
3	7.00	- 8.00	0.60	653	- 8.0	1.6
4	2.00	- 20.00	2.00	744	+ 3.0	1.6

APPENDIX II

Table 1--Station call letters and index numbers used on text figures

Index no.	Station	Figure reference	Index no.	Station	Figure reference
AZ	Albany, New York	13	HR	Huron, South Dakota	7
BX	Burley, Idaho	13	KC	Kansas City, Missouri	7
CG	Chicago, Illinois	13	LE	LaCrosse, Wisconsin	13
CV	Cleveland, Ohio	13	LS	St. Louis, Missouri	7
DM	Des Moines, Iowa	7	MF	Medford, Oregon	13
DRN	Rome, New York	13	NQ	North Platte, Nebraska	7
ER	Erie, Pennsylvania	13	OD	Dodge City, Kansas	7

Index no.	Station	Figure reference	Index no.	Station	Figure reference
OH	Omaha, Nebraska	7, 13	405	Washington, D. C.	12
PW	Portland, Maine	13	425	Huntington, West Virginia	12
RT	Rock Springs, Wyoming	13	434	St. Louis, Missouri	12
RZ	Rapid City, South Dakota	7	469	Denver, Colorado	12
SN	South Bend, Indiana	13	486	Ely, Nevada	12
TBY	Binghampton, New York	13	493	Oakland, California	12
TDO	Detroit, Michigan	13	518	Albany, New York	12, 13
TF	Scottsbluff, Nebraska	13	520	Pittsburgh, Pennsylvania	12, 13
TL	Toledo, Ohio	13	528	Buffalo, New York	12, 13
TWT	Waterman, Illinois	13	534	Chicago, Illinois	12, 13
WD	Wichita, Kansas	7	536	Toledo, Ohio	12, 13
YX	Sioux City, Iowa	7	537	Detroit, Michigan	12
			553	Omaha, Nebraska	8, 12, 13
202	Miami, Florida	12	562	North Platte, Nebraska	12, 13
208	Charleston, South Carolina	12	567	Valentine, Nebraska	13
219	Atlanta, Georgia	12	574	Rock Springs, Wyoming	12, 13
220	Apalachicola, Florida	12	597	Medford, Oregon	12, 13
235	Jackson, Mississippi	12	606	Portland, Maine	12, 13
240	Lake Charles, Louisiana	12	643	LaCrosse, Wisconsin	13
253	San Antonio, Texas	12	657	St. Paul, Minnesota	12
265	Big Springs, Texas	12	662	Rapid City, South Dakota	12
270	El Paso, Texas	12	681	Boise, Idaho	12, 13
278	Phoenix, Arizona	12	698	Portland, Oregon	12
290	San Diego, California	12	712	Caribou, Maine	12
304	Hatteras, North Carolina	12	734	Sault Ste. Marie, Michigan	12
317	Greensboro, North Carolina	12	764	Bismarck, North Dakota	12
327	Nashville, Tennessee	12	775	Great Falls, Montana	12
340	Little Rock, Arkansas	12	785	Spokane, Washington	12
353	Oklahoma City, Oklahoma	12	793	Seattle, Washington	12
365	Albuquerque, New Mexico	12	879	Edmonton, Alberta	12
386	Las Vegas, Nevada	12			

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Transactions, American Geophysical Union Volume 27, Number VI December 1946

ATMOSPHERIC CROSS-SECTIONS OF THE STRATUS ZONE OF THE TROPICAL EASTERN PACIFIC OCEAN

Leo Alpert

Abstract--Significant features of the surface and upper-air temperature and wind circulation, cloudiness, and weather over the tropical eastern Pacific Ocean during the northern summer season are revealed by atmospheric cross-sections based on observations made on reconnaissance flights of the AAF Tropical Weather Unit in all directions from Seymour Island in the Galapagos Archipelago on August 14 to 18, 1945.

Observations of winds aloft show a shallow southerly wind flow in the lower layers, while aloft the wind flow is easterly. Temperature soundings show a low inversion that is caused by cooling of the surface air by upwelling cold water and subsidence in the South Pacific anticyclone.

Stratiform clouds which form below the inversion cover a huge area from the west coast of South America to beyond 96°W longitude, the westernmost limit of the observations. Areal distribution of the stratiform clouds and associated phenomena over the tropical eastern Pacific Ocean is shown by analyzed charts containing a dense network of observations from over the Ocean made by patrol aircraft during 1942 and 1943.

Introduction--During the period July to October 1945, personnel of the AAF Tropical Weather Unit at Howard Field, Panama Canal Zone, conducted weather orientation reconnaissance flights over the tropical eastern Pacific Ocean. Student forecasters made daily flights in two C-47 aircraft modified as "flying classrooms," which were provided with radar storm-detection equipment, radio altimeters, psychrometric equipment, and extra astrodomes to facilitate visual observation. The following records were maintained on each flight: (1) An atmospheric cross-section; (2) weather-distribution chart; (3) radar-observation record; and (4) psychrometric data. These records were reproduced on a reduced scale and published in booklet form, titled In-Flight Observations of the Intertropical Convergence near Panama, AAF Tropical Weather Unit, Howard Field, Panama Canal Zone, October 1945. All the original records and observational data were filed with the Department of Weather, AAF Technical School, Chanute Field, Illinois. No attempt is made in the published booklet to analyze the data presented. As stated in the Introduction, "it was considered more desirable merely to list the observations without attempting to make perhaps questionable explanations, leaving them to be covered by research papers of this and other organizations."

The following analysis of the cross-sections made in the "stratus zone" of the tropical eastern Pacific Ocean on the flights from August 14 to 18, 1945, is based upon the author's research and analysis of surface and patrol aircraft weather reports from the area during 1942 and 1943 [see "References" at end of paper, ALPERT, 1946 a, b, and c] and personal experience forecasting for flights over the area during 1941-1943.

Figure 1 shows the routes flown on each day. It is apparent that a coverage in all directions from Seymour Island in the Galapagos Archipelago was obtained on these flights made on successive days. On August 14, 1945, the plane departed from Salinas, Ecuador, at $12^{h}53^{m}$ GCT and landed at Seymour Island in the Galapagos Archipelago at $17^{h}15^{m}$ GCT. The cross-section for this flight is shown in Figure 2. On August 15, 1945, the plane left Seymour Island at $18^{h}05^{m}$ GCT and was flown southward to 4°42′S along 90°18′W, returned along the same route, and landed on Seymour Island at $22^{h}57^{m}$ GCT. The cross-section for this flight is shown in Figure 3. On August 16, 1945, the plane departed at $13^{h}30^{m}$ GCT, and was flown westward along the Equator to 96°12′W, returned along the same route, and landed at $19^{h}17^{m}$ GCT. The cross-section for this flight is shown in Figure 4. On August 17, 1945, the flight departed from Seymour Island at $12^{h}43^{m}$ GCT and was flown northward along 90°12′W to 4°00′N, returned along the same route, and landed at $16^{h}21^{m}$ GCT. The cross-section for this flight is shown in Figure 5. On the last day, August 18, 1945, the plane departed from Seymour Island at $15^{h}34^{m}$ GCT and landed at Talara, Peru, at $20^{h}08^{m}$ GCT. The cross-section for this flight is shown in Figure 6. The flight path is shown by a solid line with arrowheads pointing in the direction of flight. The vertical scale of the cross-section is in thousands of feet above sea level.

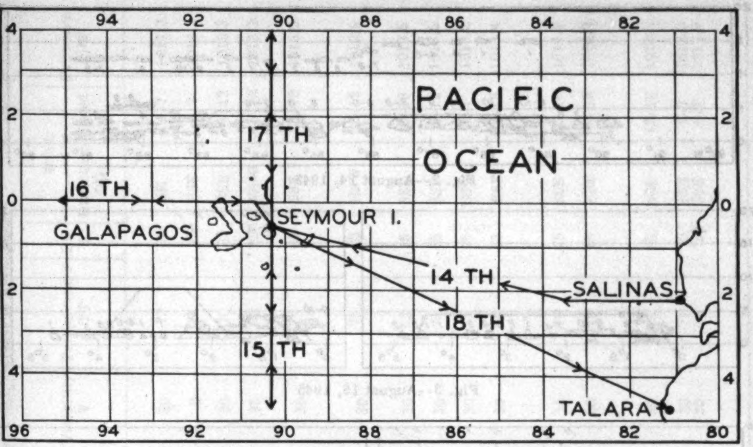


Fig. 1--Weather reconnaissance routes over the tropical eastern Pacific Ocean, August 14-18, 1945

The atmospheric cross-sections show the clouds observed on the course and within ten to 15 miles on either side. Significant clouds farther off the course are shown by dotted lines. Since it was believed that the height of the cirrus clouds could not be estimated accurately, only the coverage of cirrus clouds is indicated along the top of the cross-section by slant lines and numbers. The small Arabic numerals near the clouds indicate the number of tenths of sky covered by the respective cloud type shown. Weather phenomena are indicated by international symbols.

Analysis of the cross-sections; clouds--In all the cross-sections, the stratiform clouds are the predominant type of low clouds, and are distributed in one or more layers. On flights along the coast of South America between Panama, Salinas, Ecuador, and Talara, Peru, in 1942, the author observed two and three layers of stratiform clouds. The weather reports from the aircraft patrols during 1942 and 1943 indicate that this is a characteristic condition.

The general base of the stratiform clouds is at approximately 1000 to 2000 ft above sea level, and the top at 3000 to 4000 ft. However, on the cross-section for the flight from Seymour Island to 4°N (see Fig. 5), the general cloud top is somewhat higher than on the other routes, averaging 4000 to 7000 ft. Especially interesting is the fact that on the return flight the maximum height of cloud tops was at 4°N, the top lowering southward to the Island. This feature will be discussed later in some detail.

Some cumulus humulis clouds with tops below 4000 ft are present on all flights. On August 17, 1945 (see Fig. 5), clouds with a slight vertical development are shown between 2° and 4°N. The tops are 5000 to 7000 ft above sea level. R. H. Simpson, who participated in these flights, has informed the author that these clouds should not be considered as true cumulus congestus clouds, but rather as stratiform clouds with swelling tops.

For the most part, the low clouds are broken to overcast, and there is little variation in cloud structure observed over the ocean on the return flights over the same route. However, over Seymour Island the clouds show some diurnal variation.

The synoptic observations for Seymour Island on August 14 to 18, 1945, are tabulated in Table 1 for comparison with conditions over the adjacent ocean. Note that the stratocumulus clouds at Seymour Island have a slightly higher base than the stratiform clouds over the open ocean. The diurnal variation of the stratocumulus deck at Seymour Island is analyzed in some detail, and the meteorological elements for two typical days during the stratus season are shown in Table 3 of an article by the author [ALPERT, 1946 b].

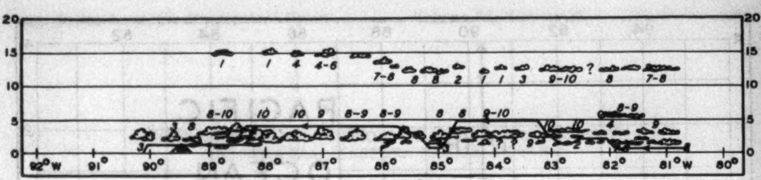


Fig. 2--August 14, 1945

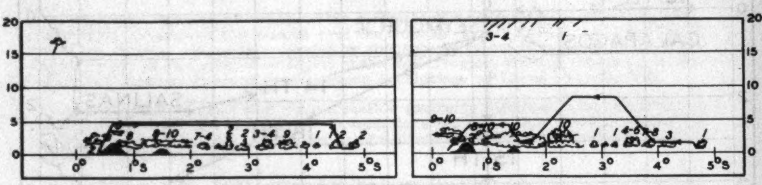


Fig. 3--August 15, 1945

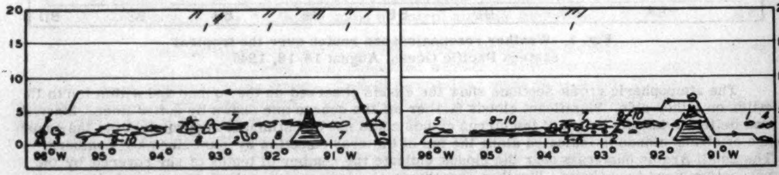


Fig. 4--August 16, 1945

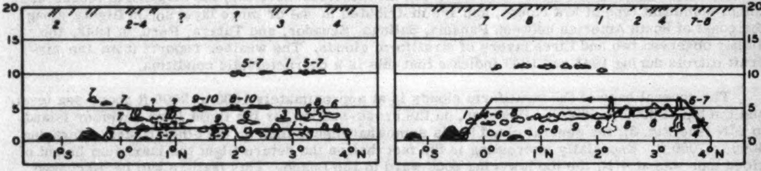


Fig. 5--August 17, 1945

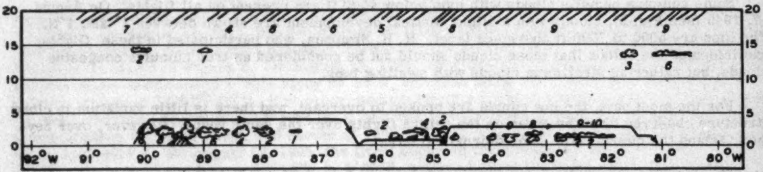


Fig. 6--August 18, 1945

Atmospheric cross-sections

Table 1--Synoptic observations, August 14-18, 1945, Seymour Island, Galapagos Archipelago

Day	Time (GCT)	Clouds								Weather		Visibility V	Temperature TT	RH U	Wind		Pressure PPP
		Type[a]			Direction	Height		Amount		Current ww	Past W				Direction DD	Speed F	
		C_L	C_M	C_H		h	hh	N_h[b]	N								
	h m					ft	ft										
14	00 30	Sc	N	N	E	1968-3280	2500	7-8	7-8	Cloudy	Overcast	30	73	75	SE	4-7	1011.2
14	06 30	Sc	N	Ci	C	1968-3280		10	10	Ugly threatening sky	Sandstorm	0	72	75	SSE	4-7	1014.2
14	12 30	Sc	Ac	Ci	N	1968-3280		9	Sky obs.	Cloudy	Overcast	30	70	85	SSE	8-12	1013.2
14	18 30	Sc	N	N	S	1968-3280	2500	9	9	Cloudy	Overcast	30	78	65	WNW	13-18	1013.2
15	00 30	Sc	N	Ci	SE	1968-3280	2500	10	10	Overcast	Overcast	30	74	65	SSE	13-18	1012.5
15	06 30																
15	12 30																
15	18 30	Sc	N	Ci	C	1968-3280		2-3	7-8	Cloudy	Overcast	30	78	65	NNW	8-12	1012.9
16	00 30	Sc	N	Ci	C	1968-3280	2800	4-6	7-8	Cloudy	Overcast	30	72	85	SSE	13-18	1012.5
16	06 30	Sc	N	N	SE	1968-3280	2000	10	10	Cloudy	Overcast	30	70	85	SSE	8-12	1013.5
16	12 30	Sc	N	N	SE	1968-3280	3000	10	10	Overcast	Overcast	30	71	75	SSW	4-7	1013.2
16	18 30	Sc	N	N	SE	3281-4920		7-8	7-8	Light, continuous rain	Overcast	30	78	65	ESE	13-18	1013.4
17	00 30																
17	06 30	Sc	Ac	N	E	1968-3280		2-3	10	Overcast	Overcast	30	71	75	SSE	13-18	1014.9
17	12 30	Sc	Ac	Cc	SW	1968-3280		2-3	10	Overcast	Overcast	30	70	85	ESE	8-12	1014.7
17	18 30																
18	00 30	Sc	Ac	N	S	3281-4920		7-8	10	Overcast	Overcast	30	73	65	SSE	13-18	1012.5
18	06 30	N	N	Ci	C				10	Cloudy	Cloudy	30	71	75	SSE	4-7	1014.9
18	12 30	Sc	Ac	N	S	1968-3280		2-3	10	Overcast	Overcast	30	70	75	SSE	4-7	1013.9
18	18 30																

[a] N = none

[b] In tenths

Middle clouds were present on the flight from Salinas, Ecuador, to Seymour Island on August 14, 1945, between 12,000 and 16,000 ft; to the north of Seymour Island, between 10,000 and 12,000 ft, on the flights from Seymour Island to 4°N on August 17, 1945; and on the flight from Seymour Island to Talara, Peru, on August 18, 1945, between 13,000 and 15,000 ft. Except for August 14, 1945, the middle clouds were present on only a small section of the route. Note the altocumulus clouds observed at Seymour Island in Table 1.

High clouds (shown by slant lines) were observed on all flights except that of August 14, 1945, between Salinas and Seymour Island. Note the cirrus and cirrocumulus clouds observed at Seymour Island in Table 1.

Analysis of the cross-sections; winds--Since the intertropical convergence zone was located north of 6°N throughout the period August 14 to 18, 1945, all the flights were made in the southern trade or southern monsoon wind streams.

Surface winds were estimated in flight by visual observation of the whitecaps on the ocean surface. The 20 observations of surface-wind directions (see Fig. 7) varied between SW and SE. Most directions were SSW, S, or SSE. The SW direction was most frequent on the flight north of the Equator on August 17, 1945, illustrating the veering of the southern trade wind as it becomes the southern monsoon wind north of the Equator [ALPERT, 1946 a and c]. The wind speed was usually estimated to be 12 to 14 knots.

Surface winds at Seymour Island are shown in Table 1. Note the land- and sea-breeze wind shift.

Winds at flight level, determined by visual double-drift methods in flight, are accurate to within about five mph (vector error).

Of the twelve observations made between 700 and 1600 ft above sea level (see Fig. 7), eleven showed a direction between 160° and 190° [90° = east, 180° = south, etc.], and one showed a direction of 202°. Wind-speeds were between eight and 15 knots, except for one of 17 knots.

Of eight observations between 2300 and 5000 ft (see Fig. 7) one direction was 5°, one 25°, two 70°, three between 213° and 270°, and one 320°. The wind speeds varied between three and 13 knots, with the majority between three and seven knots.

Five observations of the wind at 7500 or 8000 ft (see Fig. 7) showed a direction between 50° and 100°, and a speed between two and nine knots.

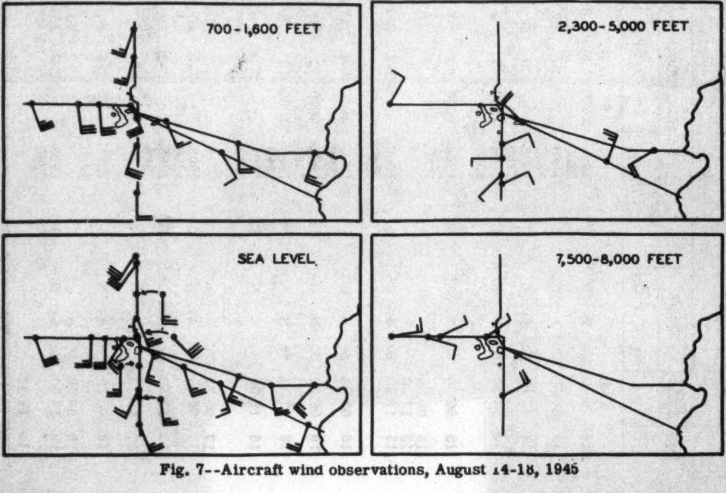


Fig. 7--Aircraft wind observations, August 14-18, 1945

Table 2--Pilot balloon observations, August 14-18, 1945, Seymour Island, Galapagos Archipelago

Altitude	Aug. 14 $10^{h}00^{m}$	Aug. 15 $10^{h}00^{m}$	Aug. 15 $16^{h}00^{m}$	Aug. 15 $21^{h}00^{m}$	Aug. 16 $04^{h}00^{m}$	Aug. 16 $10^{h}00^{m}$	Aug. 16 $16^{h}00^{m}$	Aug. 17 $04^{h}00^{m}$	Aug. 17 $10^{h}00^{m}$	Aug. 17 $16^{h}00^{m}$	Aug. 17 $22^{h}00^{m}$	Aug. 18 $04^{h}00^{m}$	Aug. 18 $10^{h}00^{m}$	Aug. 18 $16^{h}00^{m}$	Aug. 18 $22^{h}00^{m}$
ft															
16,000	...	...	...	1116	...	...	...	...	...	...	...	...	...	...	...
15,000	...	...	...	1114	...	...	...	...	...	...	...	...	...	...	...
14,000	...	...	...	0816	...	...	...	...	...	...	...	...	...	...	...
13,000	...	...	...	0920	...	...	...	...	...	...	...	...	...	...	...
12,000	...	...	...	1115	...	...	...	...	...	...	...	...	...	...	...
11,000	...	...	...	1115	...	...	...	...	...	...	...	...	...	...	...
10,000	...	...	...	1116	...	...	...	...	...	...	...	...	...	...	1202
9,000	...	...	...	0909	...	...	...	...	...	...	...	...	...	...	...
8,000	...	...	...	0706	...	...	...	...	...	1605	...	1013	...	...	1708
7,000	...	...	...	0807	...	...	...	...	...	...	...	...	...	...	...
6,000	...	1104	...	0903	...	...	...	1705	...	1109	...	1320	...	3010	2109
5,000	...	0003	...	0304	...	...	...	...	...	...	...	...	...	...	...
4,000	...	3504	...	1201	1101	...	2705	3003	...	2408	...	2813	...	2107	2313
3,000	...	2405	...	2605	...	...	2207	3003	2305	1912	...	...	2705	...	...
2,000	1805	1909	1614	2006	2006	1908	1806	1912	2010	1711	2007	1808	2006	1709	2209
1,000	1714	1518	1517	1608	...	...	1618	1912	1812	1613	...	...	1607	...	...
Surface	1209	1612	1213	1508	1612	1608	1216	1612	1610	1615	2008	1512	1607	2205	1613

Table 3--Temperature soundings, °C, August

Altitude	Station							
	Ocean, 01°42′S, 84°42′W, Aug. 14^{a}	Salinas, Ecuador, 02°12′S, 81°00′W, Aug. 14	Seymour Island, 00°28′S, 90°18′W, Aug. 15	Ocean, 00°00′, 90°30′W, Aug. 16^{b}	Ocean, 00°00′, 92°18′W, Aug. 16	Ocean, 00°00′, 94°36′W, Aug. 16	Ocean, 00°00′, 96°00′W, Aug. 16^{a}	Ocean, 01°12′N, 90°24′W, Aug. 17
ft	°C	°C	°C	°C	°C	°C	°C	°C
8000	..	12	11	14	15	15	14	..
7000	..	14	13	15	..	..	..	..
6000	..	15	15	18	..	..	..	..
5000	20	16	16	18	..	..	..	..
4000	20	17	18	19	..	..	..	..
3000	19	16	18	19	..	..	..	..
2000	18	15	18	19	..	..	..	..
1000	20	18	21	20	..	..	21	20
Surface	..	22	22	..	..	..	..	..

a = Descent b = Ascent

The pilot-balloon observations made at Seymour Island on August 14 to 18, 1945, were tabulated in Table 2 for comparison. The wind directions and speeds observed at Seymour Island are very similar to those observed by the aircraft in flight. The 21^{h}00^{m} GCT observation for August 15, 1945, is typical of average conditions. Thus, there is evident a shear of the wind direction from southerly at sea level up to 2000 or 3000 ft, becoming northeasterly or easterly above 6000 ft. The transition zone between the two wind streams is found at about 3000 to 5000 ft, where the wind direction is variable, with a westerly direction quite frequent. This is in accord with the findings of the author in a more detailed analysis of the wind structure of this area [ALPERT, 1946 a and c].

Analysis of the cross-sections; temperature--Temperature soundings which were made by the student weather forecasters while in flight are tabulated in Table 3 and Figure 8. A "free-air" thermometer was used, and the observations were uncorrected. Since the planes were flown at about 120 to 150 mph, a correction of 1°C is probably reasonable. In addition, temperature observations aloft taken from the radiosonde observation for August 14 and 18, 1945, at Salinas, Ecuador, and for August 15 and 18, 1945, at Seymour Island are shown in Table 3 and Figure 8. A radiosonde observation for the stratus season at Seymour Island is shown in the article by the author on Seymour Island [ALPERT, 1946 b].

The temperature soundings in Table 3 and Figure 8 clearly illustrate the presence of a temperature inversion over the ocean and at both Salinas, Ecuador, and Seymour Island below the 5000-foot level. On the 14th, over the ocean, the base of the inversion lies between 2000 and 3000 ft, on the 14th at Salinas between 2000 and 3000 ft, on the 15th at Seymour Island between 2000 and 4000 (here an isothermal layer), on the 17th over the ocean between 4000 and 5000 ft (also an isothermal layer), on the 18th over the ocean between 3000 and 4000 ft, at Seymour Island between 3000 and 4000 ft, and at Salinas, Ecuador, between 2000 and 3000 ft.

It is noteworthy that the southerly flow from sea level up to 2000 or 3000 ft is below the base of the temperature inversion.

The existence of the stratiform clouds in two to three layers below the main inversion base indicates there is actually a multiple-type inversion which the temperature measuring instruments are not sufficiently sensitive to detect. (Of 86 radiosonde observations made at Salinas, Ecuador, during May to July, 1944; 55 per cent showed a single inversion present below 5000 ft above sea level, 36 per cent showed a double inversion, one per cent a triple inversion, two per cent an inversion or isothermal layer at the surface, and six per cent showed no inversion present below 5000 ft above sea level. The inversions centered about the 2300-foot level and the 5000-foot level.)

Of special interest is the temperature increase on the 17th at the 1000-foot level northward from the Equator, and the temperature decrease on the 18th at the 1000-foot level southward from the Equator.

14-18, 1945, tropical eastern Pacific Ocean

Station							
Ocean, 02°36′N, 90°24′W, Aug. 17	Ocean, 03°54′N, 90°24′W, Aug. 17[b]	Ocean, 01°48′N, 90°24′W, Aug. 17	Ocean, 00°30′S, 90°00′W, Aug. 18[b]	Ocean, 01°18′S, 88°12′W, Aug. 18	Ocean, 02°24′S, 86°00′W, Aug. 18	Seymour Island 00°28′S, 90°18′W, Aug. 18	Salinas, Ecuador, 02°12′S, 81°00′W, Aug. 18
°C	°C	°C	°C	°C	°C	°C	°C
..	..	..	..	..	..	12	10
..	..	..	..	..	..	15	11
..	17	19	..	20	..	17	12
..	18	..	..	..	..	17	13
..	18	..	19	..	..	18	15
..	20	..	17	..	..	14	15
..	21	..	19	..	..	17	13
22	23	..	22	..	19	20	15
..	..	..	..	..	..	23	20

Climatic controls--The presence of stable cloud forms below the temperature inversion at the Equator, and the lack of precipitation or clouds of vertical development may at first glance be surprising to those unfamiliar with climatic controls operating in this section of the tropical eastern Pacific Ocean. There is, however, a logical explanation.

Divergence between the Peruvian Coastal Current and the coast of South America, and in the South Equatorial Current south of the Galapagos Islands results in upwelling of cold water in these areas. The cold water is carried along the coast of Peru and Ecuador and past the southern Galapagos Islands [UNITED STATES HYDROGRAPHIC OFFICE, 1942; SCHOTT, 1935; SVERDRUP, 1942]. The monthly surface-temperature chart of the Eastern Pacific Ocean for August (see Fig. 9) shows a narrow zone of relatively cold water along the coast of South America, and extending westward across the Pacific Ocean between the Equator and 5°S. The ocean-surface temperature increases rapidly between the Equator and 5°N. North of 5°N, the ocean-surface temperature is relatively uniform.

The abnormally low free-air temperatures on the west coast of South America and in the Galapagos Islands are directly attributed to the cooling of the lower layers of the atmosphere by the cold ocean surface [ALPERT, 1946 b]. The air that is cooled over the cold ocean waters south of the Equator retains relatively low temperatures far north of the original source of cooling. For example, Tumaco at about 1°40′N on the west coast of Colombia has a Southern Hemisphere temperature and rainfall regime; the coldest and driest months occur in the northern summer [ALPERT, 1946 c]. Culpepper Island at 1°40′N in the Galapagos Archipelago likewise has a Southern Hemisphere temperature and rainfall regime [ALPERT, 1946 b]. Free-air temperature charts in the Atlas of Climatic Charts of the Oceans [UNITED STATES WEATHER BUREAU, 1938] show that in the area 0° to 5°N the minimum mean monthly temperature is recorded during the northern summer season. A summary of the temperature reports (to be published at a later date in the *Bulletin of the American Meteorological Society*) from the patrol aircraft observations made between Guatemala in Central America and Seymour Island during 1942 and 1943 indicates that the low temperatures are retained by the southern monsoon to approximately 3°N, on the average, in the layer between sea level and 2000 ft above sea level. CHAPEL [1934] found that in the Panama Canal Zone during the northern summer, which is actually the hurricane season, days with constant southerly winds are 2°.9 F cooler at the surface in Cristobal on the Caribbean side, and 2°.5 F cooler in Balboa on the Pacific side, than days with constant northerly winds; thus, it appears that the southern monsoon may retain a relatively low temperature to at least about ten degrees north of the Equator.

In a previous article [ALPERT, 1946 b] it was explained that during the northern summer the cooling of the air in contact with the cold ocean surface and subsidence in the South Pacific high pressure cell causes a low temperature and moisture inversion to form with an average base of 3000 to 4000 ft and a top at 5000 to 6000 ft at Seymour Island.

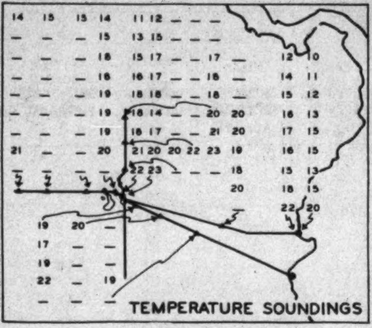


Fig. 8--Temperature soundings, August 14-18, 1945

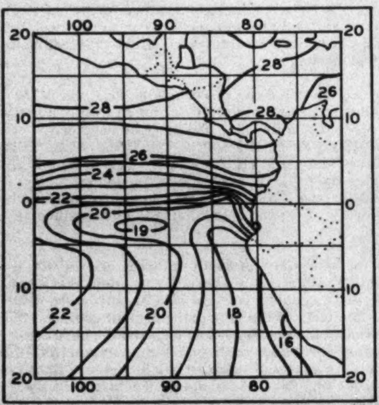


Fig. 9--August ocean-surface isotherms for the eastern Pacific Ocean [from SVERDRUP, 1942, Chart II, Prentice-Hall]

Stratiform clouds, composed mostly of stratocumulus, form below the inversion and produce a broken to overcast layer over the ocean throughout the day, being best developed in the early morning.

Reports from the pilots on the aircraft patrols during the stratus season (May-December) of 1942 and 1943 indicate that the broken to overcast stratiform clouds cover a huge area from the coast of South America to at least 96°W, the westernmost limit of the patrols, and from 7°S, the southernmost limits of the patrols, to approximately 5°N between 85°W and 96°W. The area extends a degree or two farther south along the coast of South America.

According to MURPHY [1939], the leaden stratus sky extends north of the Equator along the coast of Ecuador to Cape San Francisco at 0°40'N. However, during a flight from Salinas, Ecuador, to Albrook Field, Panama Canal Zone, in June 1942, the author observed a nimbostratus overcast at 300 to 400 ft with continuous drizzle all the way from Salinas (2°12'S) to approximately 3°N off the coast of Ecuador and Colombia. Pilots frequently report the stratiform clouds to 3°N off the coast.

Between 90°W and 96°W the height of the top of the stratiform layer, the base of the inversion south of the Equator, is approximately 2000 to 3000 ft, increasing to 3000 to 4000 ft at the Equator, and 5000 to 7000 ft at 5°N. Pilots flying northward from Seymour Island just above the top of the stratiform layer have frequently reported that the top of the cloud layer gradually increases in altitude northward to the intertropical convergence zone where heavy cumuliform clouds towering to great heights are encountered. Many have said that it is a very smooth "uphill" flight.

The increasing of the height from south to north of the inversion base is probably mainly the result of increased heating from below as the southern monsoon encounters warmer and warmer water while moving northward (see Fig. 7) and of decreased subsidence farther away from the center of subsidence in the South Pacific anticyclone. North of 5°N the inversion is usually destroyed by heating from below combined with decreased subsidence and convergence in the intertropical and secondary convergence zones. It is believed that the lines of cumuliform clouds which develop where the inversion is destroyed have been mistakenly identified by FLETCHER [1945] as the result of the splitting of the intertropical convergence zone into two or more parallel lines of cloud build-up.

South of the Equator the characteristic precipitation forms are drizzle and mist or "garua," whereas north of the Equator, rain showers, squalls, and thunderstorms are present in addition to drizzle and "garua." The rain showers, squalls, and thunderstorms develop locally wherever the weak inversion is dissipated, as, for example, in secondary convergence zones in the southern monsoon. FLETCHER [1945] has a different explanation for these precipitation areas.

Maps of the tropical eastern Pacific Ocean during the stratus season--To illustrate the areal distribution of the stratiform clouds and other features just outlined, the weather observations

received from the aircraft patrols over the ocean on September 23, 1942, September 29, 1943, and November 16, 1942, are shown in Figures 10, 11, and 12, respectively. The station model used in Figures 10, 11, and 12 is outlined on the following page. B = Flight altitude in hundreds of feet; C_L = low cloud type, international symbol; C_M = middle cloud type, international symbol; C_H = high cloud type, international symbol; DD = wind direction at flight level; F = wind speed at flight level, a half barb equals a Beaufore Force of one unit; GG = Greenwich time of observation; H_B = height, in hundreds of feet, of base of low, middle, or high cloud above sea level; H_T = height, in hundreds of feet, of top of low, middle, or high cloud above sea level; N = amount, in tenths, of low, middle, or high cloud; TT = temperature in °C at flight level; and ww = state of weather, international symbols.

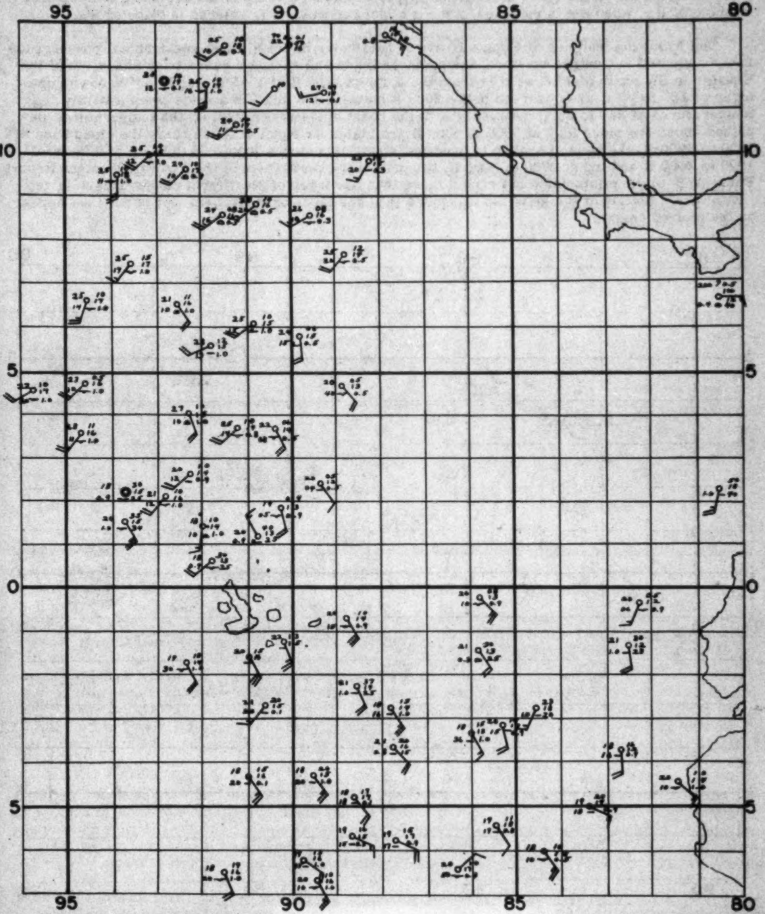
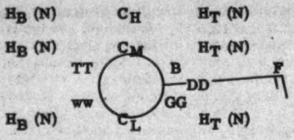


Fig. 10--Map of aircraft weather reports for the tropical eastern Pacific Ocean, September 23, 1942



H_B is reported when the plane is flying below the cloud deck, and H_T is reported when the plane is flying above the cloud deck. When H_B is reported, and H_T is not reported, N is entered in place of H_T; when H_T is reported, and H_B is not reported, N is entered in place of H_B.

The following features of Figure 10 are of particular interest: The intertropical convergence zone is located in Central America; the southern trade and monsoon veers from SSE south of the Equator to SW north of 7°N; wind is from the north at 4000 ft at 1°15'N and 90°45'W; low temperatures of 18° to 20°C are observed below 2000 ft between 3°S and 7°S and the comparatively high temperatures of 24° to 25°C between 5°N to the coast of Central America; the temperatures reported above the cloud tops at 3000 to 4000 ft are higher or equal to those below the cloud base at 1000 to 2000 ft; the base of broken to overcast stratiform clouds from 7°S to north of 5°N is at 1000 to 2000 ft and top at 2500 to 3000 ft, because of the limitations of the Aircraft Weather Report Form (WB-9) the pilots could not report more than one layer of stratiform clouds except in the "Remarks" section of the form, so that more than one layer of stratiform clouds does not appear on the plotted charts.

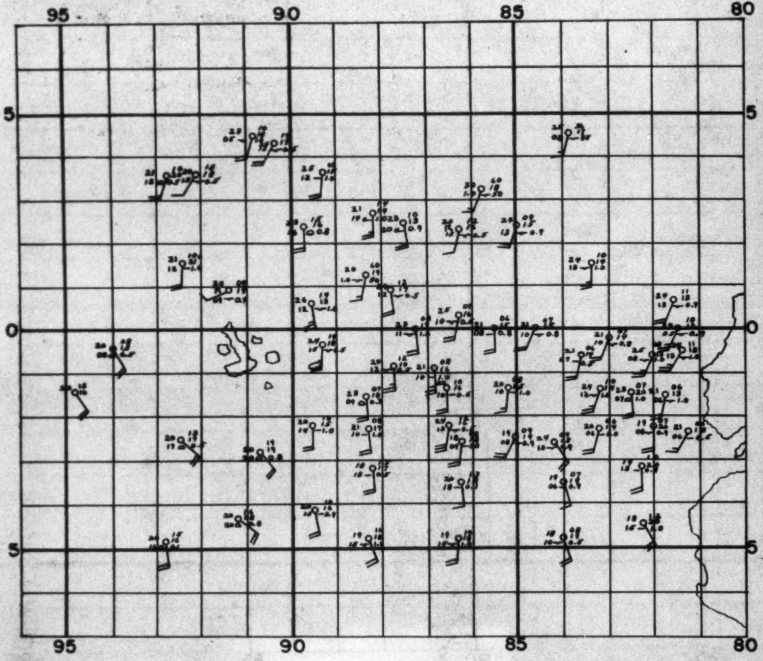


Fig. 11--Map of aircraft weather reports for the tropical eastern Pacific Ocean, September 29, 1943

The following features of Figure 11 are of particular interest: The intertropical convergence zone was located north of 7°N (the northern limit of the data received for this day), and apparently did not materially influence the weather south of 5°N; the southern trade and monsoon have a southerly direction, the southerly wind stream is apparently deep, as two reports, one north of the Equator at 6000 ft and the other at 3600 ft show the same southerly wind direction as at 1000 to 2000 ft (however, two upper wind observations at Seymour Island show a south wind at the surface and at the 2000-foot level, and an east wind at the 4000-foot level and higher); the stratus deck is lowest off the coast of Ecuador between 1°S and 3°S, where it is more or less overcast with a ceiling of 600 to 800 ft above sea level, the broken stratus deck is between 800 to 2000 ft over the rest of the

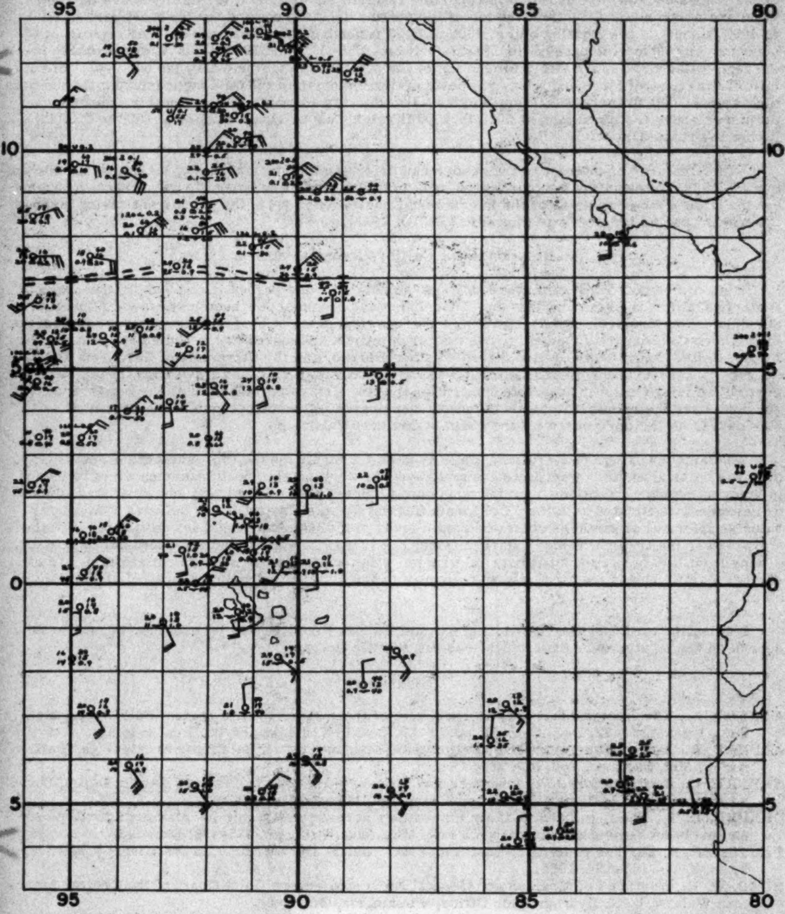


Fig. 12--Map of aircraft weather reports for the tropical eastern Pacific Ocean, November 16, 1942 area averaging highest north of the Equator; the cumulus clouds reported south of the Equator and west of 90°W are probably stratocumulus clouds rather than cumulus; lowest temperatures (18° to 20°C) between sea level and 2000 ft are recorded south of the Equator; two thunderstorms are reported north of the Equator.

The following features of Figure 12 are of particular interest: The intertropical convergence zone, shown as a double dashed line, is located at approximately 7°N along a marked wind shift below 2000 ft (note also the cumulonimbus clouds, rainfall, and thunderstorm in the convergence zone); south of the intertropical convergence zone all the wind observations from sea level to 2000 ft above sea level (generally below the cloud base) are southerly in direction, whereas all the observations but two (one of which is reporting rainfall) above 2100 ft (generally above the cloud tops) are northerly in direction; the top of the stratus deck is reported for the most part at 2000 to 4000 ft south of the Equator and at 4000 to 5000 ft north of the Equator (the three reports of 4000 and 4500 ft for the base of the stratus between 0° to 3°N and 92°W to 96°W are probably incorrect, as they are more likely for the top of the stratus and not the base); the one report of rainfall off the coast of Peru and the two reports of drizzle north of the Galapagos Islands; the temperature below 2000 ft increases from south of the Equator to north of the Equator, the temperatures above the cloud tops at 3000 to 4000 ft are higher or equal to those at 1000 to 2000 ft (below the cloud bases).

Other features of interest to the reader can be determined by analysis of the maps. On November 16, 1942, the situation is complicated by the fact that modified polar air was present throughout the trade wind zone north of the intertropical convergence zone, the polar front having invaded the tropics during the previous four days [HURD, 1943].

Relation to the California coastal stratus

It should be noted that climatic conditions similar to those present along and off the coast of Southern California prevail in this area. Considerable progress has been made toward an understanding of the formation and dissipation of the low stratus associated with temperature inversions in Southern California as a result of the research project sponsored by the United States Army Air Force, United States Navy, United States Weather Bureau, and the University of California at Los Angeles in 1944 and 1945 [NEIBERGER, 1944; NEIBERGER, BEER, and LEOPOLD, 1945]. However, little information is available concerning the low stratus associated with the temperature inversions over the open ocean beyond the land-sea breeze influence because of the paucity of suitable data from the open ocean off the coast of Southern California.

The hourly weather observations made by patrol aircraft for the two-year period 1942-1944 over the tropical eastern Pacific Ocean and along the west coast of South America could be useful in studying stratus conditions over the open ocean. Based on a preliminary survey of these data by personnel associated with the "California Coastal Stratus Project" it is believed that much valuable information could be obtained from a study of the physical processes associated with the stratus over the tropical eastern Pacific Ocean. It is also suggested that the coordination of the climatological data accumulated over that region with those from the subtropical and mid-latitude eastern Pacific Ocean, particularly with respect to the distribution and frequency of stratus, would be useful.

It is anticipated that the "California Coastal Stratus Project" will be expanded to include research on the stratus over the tropical eastern Pacific Ocean.

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GEOMAGNETIC SECULAR CHANGE DURING PAST EPOCHS

E. H. Vestine, L. Laporte, and C. Cooper

Abstract--The present paper concerns the description of geomagnetic secular change during the past four decades, and its preliminary interpretation in relation to the origin of the Earth's main field and its secular change. The work is based mainly on extensive magnetic surveys over land and sea over the past 40 years, carried out by or in cooperation with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, with final reductions financed by the United States Navy.

Isoporic world charts giving secular change for four epochs 1912.5, 1922.5, 1932.5, and 1942.5, for each of the seven magnetic elements were drawn. This work was preparatory to construction of new isomagnetic world charts in declination (D), horizontal intensity (H), inclination (I), north intensity (X), east intensity (Y), vertical intensity (Z), and total intensity (F) for epoch 1945. Included also in this work are spherical harmonic analyses of these world charts, the computation, using automatic machines, of the charted values to heights up to 5000 km above the Earth's surface, and likewise the computation of a few equivalent electric-current systems within the Earth. This project is now nearing completion and will be described subsequently. It is the purpose here to present a few indications of the results of this work; it is also well to emphasize that the writers here are presenting the work of a team of many workers who have contributed.

There are presented here new charts for the north ($\dot{X}$-) and east ($\dot{Y}$-) components of secular change, along with calculated equivalent thin current sheets at depth 2000 km within the Earth which could reproduce them.

It is tentatively suggested that the existence of secular change and at least a part of the main field is perhaps rendered possible by a crystalline condition of the Earth's mantle. The calculated current-flow patterns within the Earth show large variations in pattern and current density from one decade to the next. This must mean on the electric current hypothesis of origin of secular change large changes in electromotive forces per epoch, at probable depths within the Earth where, to the best of our present knowledge, only slow changes in physical processes with time are expected. It is suggested that if we are to retain the electric current hypothesis of origin it seems more reasonable to assume as a working basis the existence of very small changes per decade in electromotive force, in the presence of a medium of extremely high electric conductivity. This possibility seems independently supported (or at least not negated) by the calculations of electric conductivity at various depths within the Earth down to about 700 km by LAHIRI and PRICE [See "References" at end of paper, 1939], who applied the theory of electromagnetic induction to geomagnetic daily and storm-time variations.

Geomagnetic secular change, $\dot{X}$ and $\dot{Y}$, at four ten-year intervals--Geomagnetic survey data at about 2000 repeat stations and 100 magnetic observatories were graphed as a function of time for the period 1905 to 1945. The observations were reduced to the epoch of the middle of month of observation, by approximate removal of the influence of the geomagnetic variation with sunspot cycle, the annual variation, post-perturbation, and daily variation. The slopes of the graphs at epochs 1912.5, 1922.5, 1932.5, and 1942.5 were read and plotted on maps, and isopors were drawn for $\dot{D}$, $\dot{H}$, $\dot{X}$, and $\dot{Y}$. These were adjusted to mutual consistency on a basis such that the curl of the geomagnetic surface-field vanished to good approximation at the corners of each ten-degree tessera in latitude and longitude. Further adjustments, mainly over ocean and polar areas, were effected such that line integrals in $\dot{X}$ along geographic meridians and in $\dot{Y}$ along parallels of latitude vanished to good approximation.

Figures 1 to 8 illustrate the Mercator sections for the results obtained in the $\dot{X}$- and $\dot{Y}$-components at the four epochs. The accuracy of these charts is difficult to assess, but perhaps it may be hazarded that it reaches an average of about ten gammas over many land areas, but an average accuracy of less than 15 or 20 gammas is expected over most ocean and polar areas. Attention is particularly called to the rapid changes in various foci in $\dot{X}$ and $\dot{Y}$ appearing in only a decade, and the considerable differences between the charts for 1912.5 and 1942.5 after only three decades.

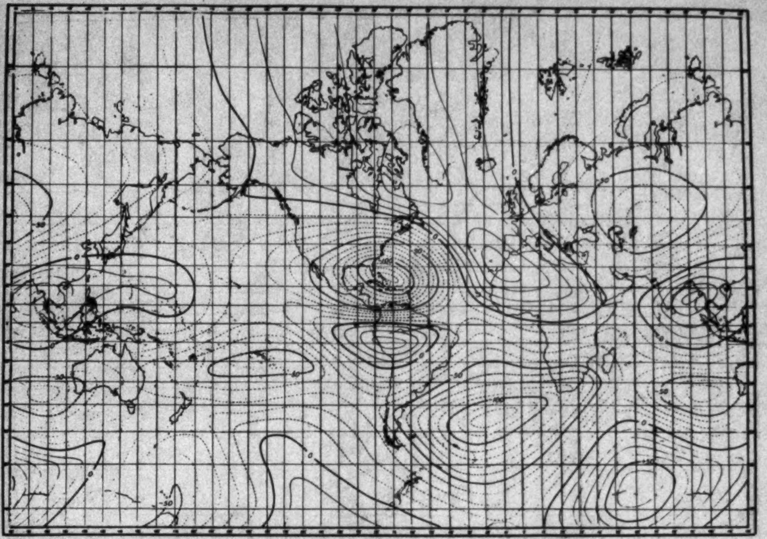

Fig. 1--Geomagnetic secular change in gammas per year, north component, epoch 1912.5

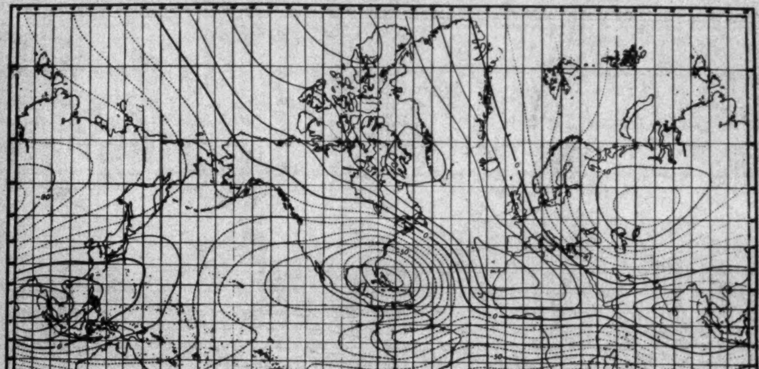

Fig. 2--Geomagnetic secular change in gammas per year, north component, epoch 1922.5

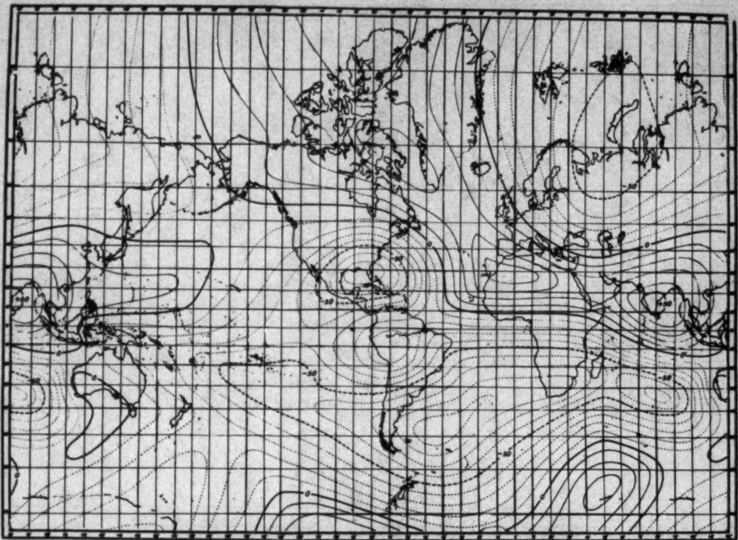

Fig. 3--Geomagnetic secular change in gammas per year, north component, epoch 1932.5

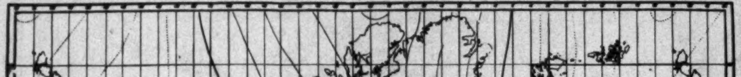

Fig. 4--Geomagnetic secular change in gammas per year, north component, epoch 1942.5

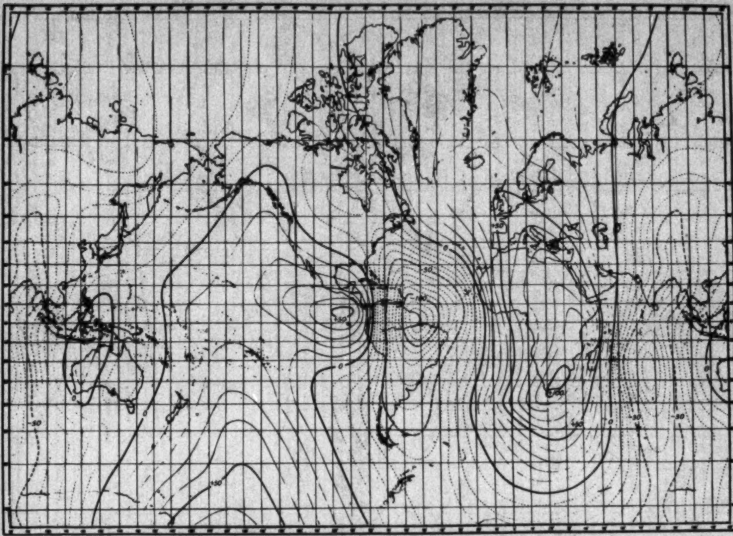

Fig. 5--Geomagnetic secular change in gammas per year, east component, epoch 1912.5

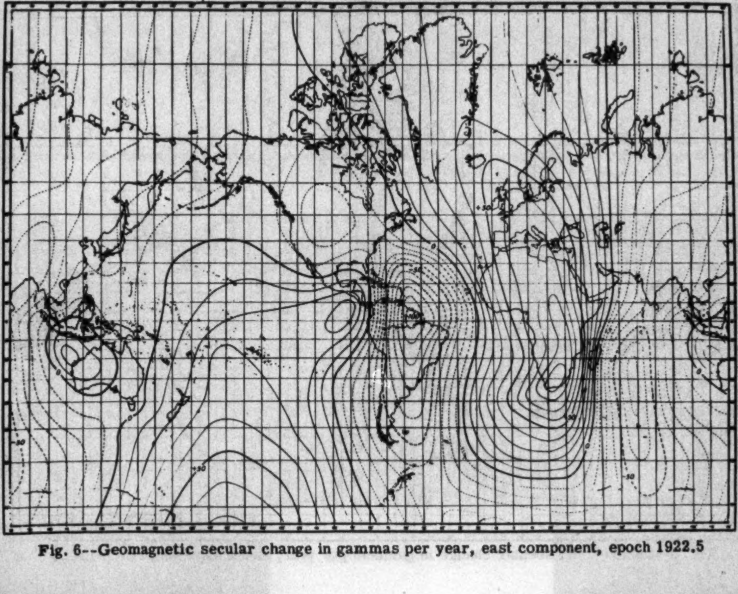

Fig. 6--Geomagnetic secular change in gammas per year, east component, epoch 1922.5

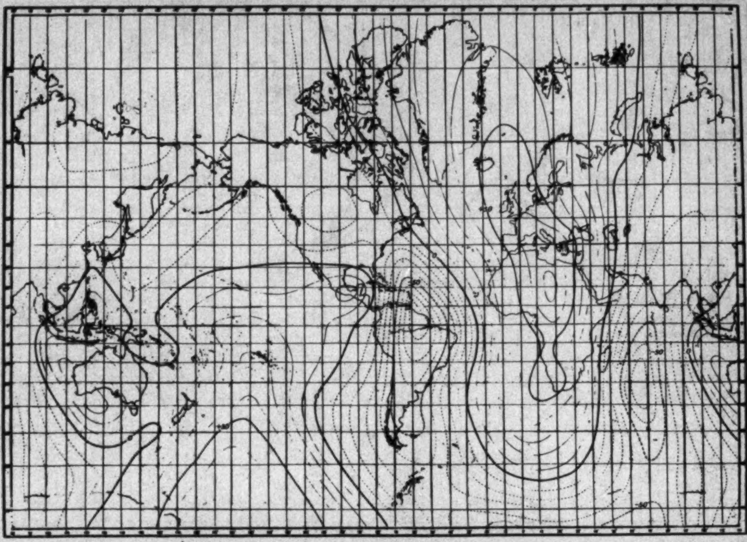

Fig. 7--Geomagnetic secular change in gammas per year, east component, epoch 1932.5

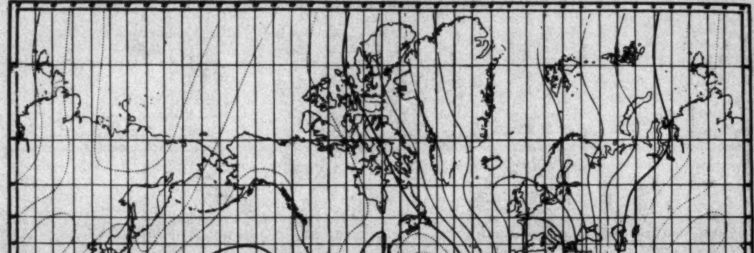

Fig. 8--Geomagnetic secular change in gammas per year, east component, epoch 1942.5

Representation by spherical current sheets concentric and internal to the Earth--Figures 9 to 12 show the current functions calculated for each epoch, assuming the secular change is entirely of internal origin and due to current flow at a depth 2000 km. These results were obtained from spherical harmonic analyses (to be reported subsequently) using International Business Machines, along with similar calculations for depths 0, 1000, and 3000 km. The current patterns for depth 3000 km are so complex that they may well represent a roughly defined lower limit in depth for which such hypothetical current patterns may be calculated in this manner. Thus, if a fairly simple current pattern is regarded as more probable than one regarded subjectively as too complex, the 3000-km pattern was rendered too complex either because of defects in the surface data analysed, or because magnetic materials or electric currents are present in sufficient quantity to destroy the conditions permitting calculation of currents. This type of consideration has previously been indicated by CHAPMAN [1935] and discussed in more detail in relation to the geomagnetic secular change and non-dipole component of the main field by McNISH [1940].

According to an assessment by SCHUSTER [1912] and subsequent recent revision of considerations regarding the difficulties in explaining the origin of the main field and its secular change on the basis of electric currents within the Earth, these difficulties are insuperable [VESTINE, TUVE, and JOHNSON, 1940]. If the electric currents are confined to a relatively thin stratum near a depth of 2000 km, the patterns of change of current flow per year may in some measure resemble those in Figures 9 to 12. Although the significance of the current functions illustrated, and the degree of their approximation to the real current system (if it exists) cannot really be assessed at all at present, it is evident that these current functions afford one of the simplest and most convenient means of representing geomagnetic secular change. Moreover, the model with change in units but not in line configuration alternatively gives at once the representation by an equivalent magnetic shell, whose field is additive per year to that of the main field for the applicable epochs.

The sense of rotation of current is counter-clockwise in higher northern latitudes and clockwise in lower southern latitudes, except for a small focus with counter-clockwise rotation in south polar regions where secular change data were poor. The irregularities in current flow in low and middle latitudes render the supposition of some degree of symmetry relative to the Earth's axis of rotation or to, say, the vertical component of the main field at these epochs scarcely compelling. However, it is clear that the current density throughout the Pacific basin is relatively smaller than it is, in general, elsewhere. The main feature is the great change in current density in some regions (such as beneath eastern South America) from one ten-year epoch to the next.

If there is a flow of the type considered near depth 2000 km, changing markedly from one ten-year epoch to the next, there should likewise be expected corresponding rapid change in electromotive forces, and in the mechanism creating them. However, if the mantle of the Earth is mainly crystalline in character, even though somewhat plastic, as suggested from various non-magnetic considerations, it seems inconceivable that any mechanism yielding electromotive forces could undergo vast differences in so short a time interval as ten years. Hence we are led to entertain the possibility as to whether in fact it is not more reasonable to suppose that the changes per year in electromotive force are very small, even though current changes per year are relatively large. This might be possible if the electric conductivity in the layer were very high.

LAHIRI and PRICE [1939] inferred from study of the geomagnetic daily and storm-time variations that the electric conductivity experiences a very rapid increase at an increasing depth 600 or 700 km, to values in excess of 10^{-11} emu as compared with 10^{-15} emu for surface rocks. They did not have available for study geomagnetic variations of longer period, which might permit inferences respecting the possible conductivity at greater depths.

In providing material for removal of the influence of various geomagnetic variations upon estimates of secular change shown in the isoporic charts, derivations were made of the annual variation for each year of the period 1905 to 1942, and of the geomagnetic variation with sunspot cycle. These variations seem best regarded not as unique phenomena characterizing the geomagnetic field but rather as averages of effects of separate storm-time variations, the average frequency of moderate or larger disturbances depending on time of year or year of sunspot cycle. But by the principle of superposition of magnetic fields the annual and sunspot geomagnetic variations should serve equally well as corresponding unique phenomena of similar period in estimating the Earth's internal conductivity at great depths. This problem is under study and will be reported upon more fully at a later date, but a grave difficulty experienced is the difficulty of obtaining sufficiently accurate values of the variations in vertical intensity.

Unfortunately the present derivations of data based on the results of magnetic observatories of the past 40 years are defective in the accuracy of measurements of vertical force, and data are

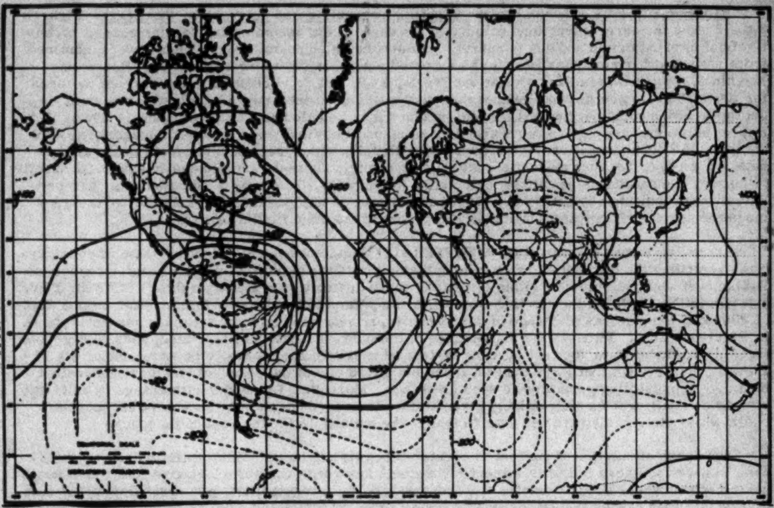

Fig. 9--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnatic secular change, epoch 1912.5

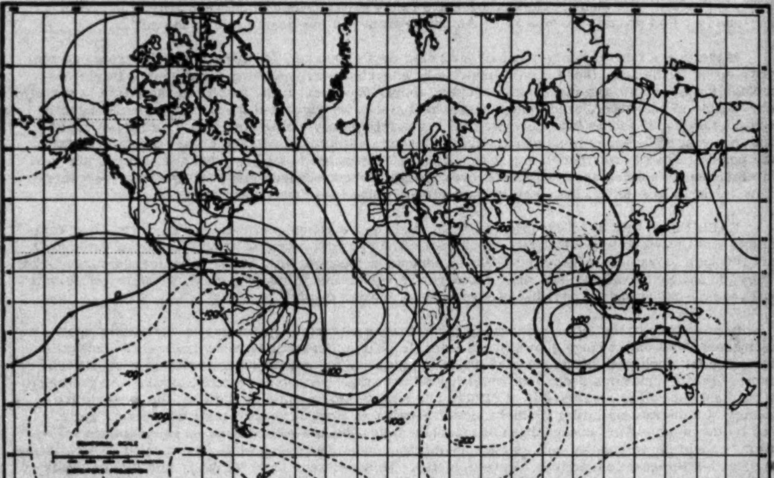

Fig. 10--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnetic secular change, epoch 1922.5

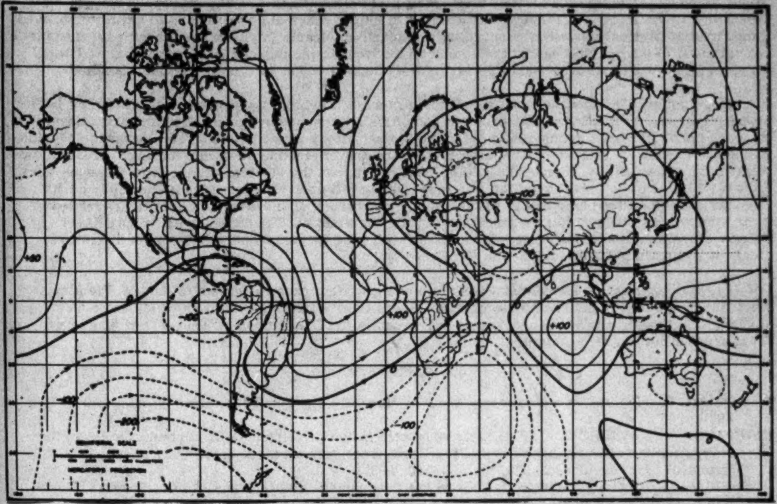
+60
-100
+100
+100
0
-100
-200
-100
0
GEOGRAPHICAL SCALE
MERCATOR'S PROJECTION

Fig. 11--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnetic secular change, epoch 1932.5

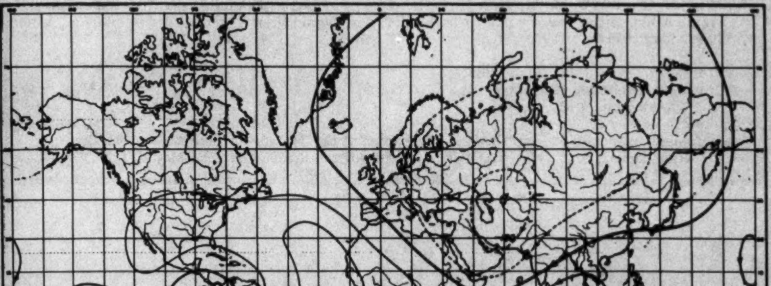
+100
+100
-100
-200
-100
GEOGRAPHICAL SCALE
MERCATOR'S PROJECTION

Fig. 12--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnetic secular change, epoch 1942.5

being reexamined from this point of view. The confidence attached to the averages obtained may perhaps only be increased through introduction in future years of observations of greatly improved standards in vertical intensity. Accordingly it seems desirable to check results with a geomagnetic variation of 27-day period now in the course of derivation; the induced currents associated with this variation would be expected to penetrate well below the 700 km level previously studied.

Conclusion--The proposal that the Earth's electric conductivity at great depths is very high merits increased attention. This problem should be approached by considering and extending inferences possible from geomagnetic data, and by laboratory experiments on high pressure physics. If the Earth's main field and its secular change are due to electric currents, however caused, flowing in the mantle, it seems likely to be imperative that the electric conductivity there be very great. If this can be established the way may then be left open to explain the main field and its secular change on the basis either of thermoelectric forces or piezoelectric forces associated with stresses existing within the supposed crystalline mantle. The stresses or variations in temperature must be subject to rapid variation with time as compared with the slow processes, such as mountain building, evinced in the Earth's crust.

Acknowledgments--The writers wish to make grateful acknowledgment to Jno. A. Fleming, Director, for support and encouragement, to Miss Isabelle Lange for the results of work on spherical harmonic analyses, and to our colleagues in the Department of Terrestrial Magnetism, Carnegie Institution of Washington.

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EMPIRICAL AND THEORETICAL RELATIONS BETWEEN WIND, SEA, AND SWELL

H. U. Sverdrup and W. H. Munk

(Contribution from the Scripps Institution of Oceanography, New Series, No. 300. This work represents results of research carried out for the Hydrographic Office and the Bureau of Ships of the Navy Department under contract with the University of California.)

Prior to the War there existed a wide gap between the theoretical knowledge of surface waves and the empirical knowledge of sea and swell, sea being defined as waves raised by the direct action of the wind, swell as waves that have emerged from a storm area and travel through regions of calm or weak winds. A few theoretical conclusions have been verified by experience. Thus, it had been established that the wind waves have, in general, the character of deep water waves for which speed, period, or length are interrelated. The speed is proportional to the period and proportional to the square root of the length:

$$C = L/T = (g/2\pi)T = \sqrt{(g/2\pi)L}$$

where C is wave speed, L wave length, T period, and g acceleration of gravity.

On the basis of these results it is safe to assume that a number of the other characteristics required by the theory apply, for instance, that the average energy per wave length is proportional to the square of the wave height (vertical distance from crest to trough), that only the wave form advances, and that the water particles move nearly in circles, the radii of which decrease rapidly with depth.

The knowledge of the generation of waves and of the advance of swell was, however, very inadequate, particularly for the purpose of forecasting sea and swell on the basis of weather maps from ocean areas. For this purpose it is necessary to know the relations between wind and sea, and the manner in which swell advances and decays.

One might believe that after a century of observations, empirical laws had been established which would answer these practical purposes, but such is not the case. Anyone who has examined

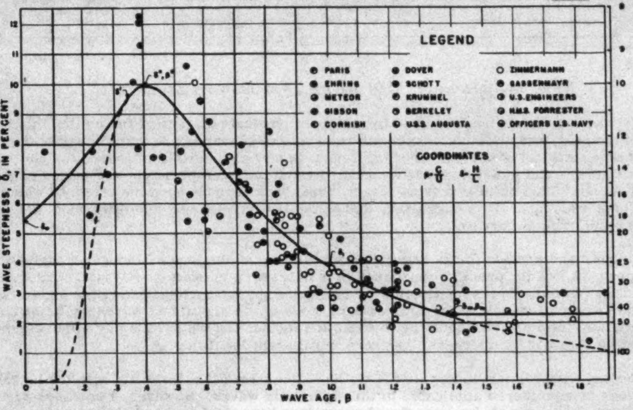

Fig. 1--Wave steepness plotted against the ratio of wave velocity to wind velocity the results of statistical compilations knows that these are incomplete and often contradictory. Thus, some authors claim that the speed of the waves never exceeds the speed of the wind that generates them; whereas others present evidence to show that the waves can travel with a speed which exceeds the wind speed up to 50 per cent. Similarly, some authors find that the wave height is proportional to the wind speed, others that it increases with the square of the wind speed, and some authors find that the steepness of the waves, as expressed by the ratio between wave height and wave length, is independent of the wind speed, others find that steepness decreases with increasing wind speed, and others again that it increases.

There are two reasons for these discrepancies. In the first place, the sea does not depend upon the wind speed only, but it also depends upon the dimensions of the water surface over which the wind is blowing, the fetch of the wind, or upon the length of time the wind has been blowing, the duration of the wind. In the second place, the wind never raises a uniform sea, that is, it does not generate a single train of well-defined waves which all have similar heights and periods. To the contrary, the wind generates a spectrum of waves ranging from ripples to large billowing seas. Furthermore, these waves travel in different directions at small angles with the prevailing wind, and the consequent crisscrossing leads to a checkerboard pattern of crests and troughs which is constantly changing. The sea is therefore always confused and it is extremely difficult to describe it by means of two single parameters, such as wave height and wave period.

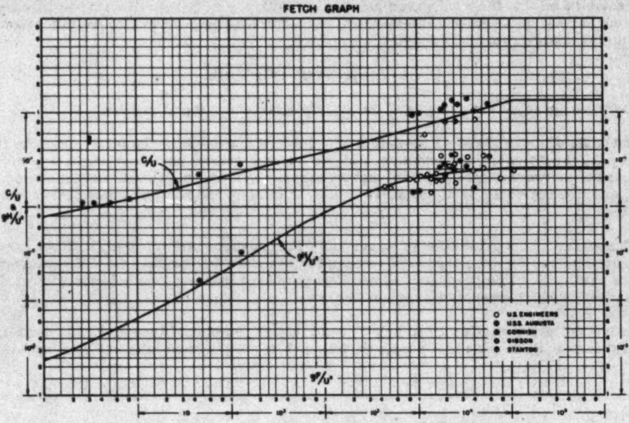

Fig. 2--Parameters C/U and gH/U^2 plotted against gF/U^2

Actually, the sea should be described by means of adequate statistical terms, but this has not been done in the past, and the true meaning of numerous observations is therefore obscure. In order to obtain consistent observations of the sea, it is now proposed to introduce the concept "significant waves," and to define these as waves having the average height and period of the one-third higher waves. This definition is not exact, because it depends upon the extent to which small waves have been recorded. It is suggested, therefore, that ripples and small waves of heights less than one ft should be disregarded.

Exact heights and periods of the significant waves can be obtained by laborious evaluations of continuous records, but for practical purposes it is necessary to make short-cuts. Experience so far indicates that an observer who attempts to determine the characteristics of the higher waves present tends to record values which approximate those of the significant waves as defined above. One of the goals of future work should be to establish methods of observation by which comparable results could be obtained by different observers in different localities.

When dealing with earlier observations, we have to assume that these apply to the higher waves present and can be considered applicable to the significant waves. However, a considerable scatter of the values may be expected, because the observations have not been made by following a standard procedure. The empirical data which are available for the establishment of rational relations between wind and sea are therefore of poor quality, but it will be shown that in spite of this they can be fitted into a consistent framework.

A consistent framework can be established by considering the manner in which waves grow by energy being transferred to the waves from the wind. This transfer takes place by two processes; by the effect of normal pressures, and by the effect of the tangential stress which the wind exerts on the sea surface. The effect of normal pressures was first examined by Jeffreys. Jeffreys points out that when the wind blows over waves that travel at a speed less than the wind speed, there will be exerted a surplus pressure against the upwind slope of the crest, whereas a deficit in pressure develops on the downwind slope. Under these conditions energy is transferred from the wind to the wave; but if the wave travels faster than the wind, the wave meets air resistance and loses energy. Jeffreys believed that energy transfer takes place by this process only, and reasoned therefore that the waves could not travel faster than the wind. However, energy is also transferred by the tangential stress (the drag) which the wind exerts on the sea surface. The effect of the drag is to speed up the motion of the particles at the wave crest and to slow down the motion of the particles at the trough, but the speed-up is greater than the slow-down, so that a net increase in energy results even if the wave moves with greater speed than the wind.

In this connection it should be remembered that only the wave form advances with a great speed; the water particles move nearly in circles and advance very slowly in the direction of wave travel.

When applying the above considerations to the growth of waves, two empirical results must be considered: (1) If the wind blows over a limited fetch, a steady state will be reached, that is, when the wind has blown for a sufficient length of time the significant waves will no longer increase in height or period anywhere in the fetch. (2) When the wind blows over an unlimited fetch, the waves will grow in height and period at the same rate in all localities.

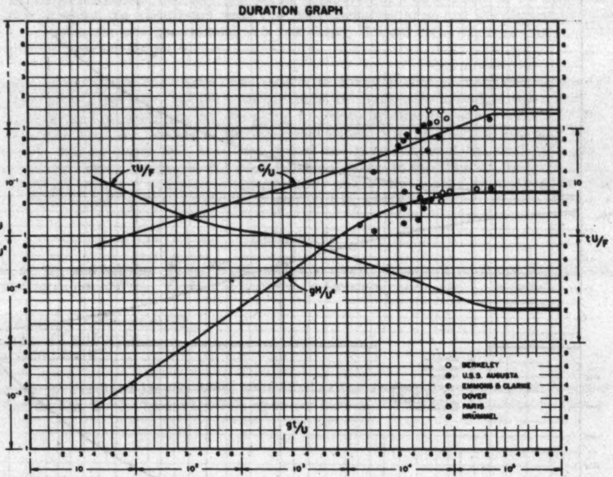

Fig. 3--Wave height and speed as functions of duration, t, and wind speed, assuming unlimited fetch

These considerations, together with knowledge of the manner in which energy advances with the wave form, lead to the establishment of two differential equations which apply to the two cases stated above, provided that the wind blows with a steady speed, U.

Steady state:

$$(C/2)(dE/dx) + (E/2)(dC/dx) = R_T \pm R_N \left.\begin{matrix} + & C < U \\ - & C > U \end{matrix}\right\} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Transient state:

$$dE/dt + (E/C)(dC/dt) = R_T \pm R_N \left.\begin{matrix} + & C < U \\ - & C > U \end{matrix}\right\} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where E is the average energy per wave length, which is proportional to H^2 (H is wave height), and R_T and R_N are the rates at which energy is transferred by the effects of tangential stress and normal pressure. Each of these equations contains two unknown variables, energy and wave speed, but energy depends upon wave height only, and the unknowns can therefore be considered as wave height and wave speed. In order to solve them, a third equation must be established, and for this purpose one has to turn to the empirical data. Certain considerations suggest that a relationship exists between wave steepness, as defined by the ratio H/L, and wave age, as defined by the ratio C/U. These two quantities are plotted against each other in Figure 1, which contains all the observations available to the authors (128 sets). The observations show a considerable scatter which at least in part can be attributed to the inconsistent manner in which they have been made, but they also show an unmistakable relationship which can be well represented by the solid curve in the graph. This curve has not been drawn simply to fit the observations, but is derived theoretically after having selected certain numerical constants to obtain a fit.

The relationship between wave steepness and wave age, which has been established in this manner, can be used in solving equations (1) and (2). The solutions can all be presented as relations between non-dimensional ratios and can be compared with observed values.

Figure 2 shows the parameters C/U and gH/U^2 plotted against gF/U^2 (F is fetch), that is, it shows wave height and wave speed as functions of fetch and wind speed, assuming unlimited duration. The range is so large that 4 × 5 cycle logarithmic paper is used. The curves represent the theoretical results, and the dots represent observations. The general agreement is satisfactory over a wide range, particularly since the observed values are of poor quality. Figure 3 shows in a similar manner the wave height and speed as functions of duration, t, and wind speed, assuming unlimited fetch, and again the agreement with observations is adequate.

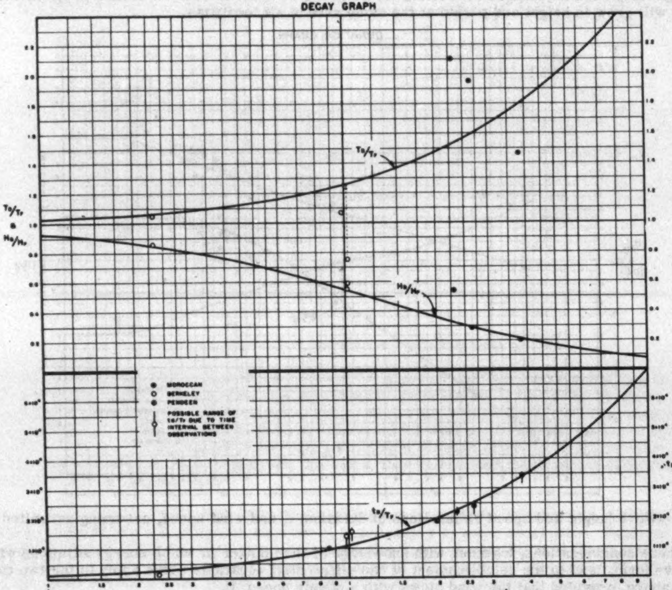

Fig. 4--Theoretical and observed values of heights, periods, and travel time in the decay area

Figure 3 contains a third curve from which one can obtain the duration needed for establishing a steady state over a given fetch. If the observed value of the parameter tU/F falls below the curve marked tU/F, a steady state has not been reached and corresponding values of H and C must be obtained from the duration graph, but if the observed value falls above the curve, a steady state has been established and values of H and C must be taken from the fetch graph.

Turning to the swell, it can first be stated that the swell is also irregular and must be described by the "significant waves." When swell advances through regions of calm it loses energy because it meets an air resistance, but no effect of tangential stress need be considered. The behavior of swell can be examined without introducing any new assumptions or constants. One arrives at the conclusion that the period increases and the wave height decreases with increasing distance from the end of the fetch. This distance is called the distance of decay, D. The ratio between period at the end of the distance of decay and at the end of the fetch, T_D/T_F, and the ratio between the corresponding wave heights, H_D/H_F, as well as the ratio between travel time and period at the end of the fetch, t_D/T_F, can all be represented as functions of the same parameter, D/gT_F^2.

Figure 4 shows the theoretical curves and the few observed values which are available for comparison. The observed heights and travel times of swell agree well with the theory, but the changes in wave period show a wide scatter. It should be noted, however, that the ratio between the periods is a ratio between two quantities which are difficult to establish, and, furthermore, that the assumed period increase enters in computing the travel time, for which reason the good agreement between observed and computed travel time confirms the conclusions as to increase in period. It should be added that actually only the values of D, T_D, H_D, and t_D are observed, and that the values of H_F and T_F have been derived from weather maps by means of Figures 2 or 3.

The relations which have been discussed here are not presented in a manner which is convenient for practical purposes, but they can all be combined in a nomogram or an alignment diagram by means of which the significant waves in the generating area and the character of the swell arriving at a distant coast can be obtained in a few steps, if wind velocity, fetch, and duration have been derived from weather maps.

The relationships shown here have been used with considerable success during the War for forecasting sea, swell, and surf, but the establishment of these relationships represents only a first step. It is hoped that attempts will be made to obtain systematic observations of sea and swell, that the reason for the scatter of the observed values will be studied, and that the forecasting technique will be improved. It is also hoped that future theoretical work will clarify several steps in the theory leading to the relationships shown in the figures, and will bring an understanding of the physical contents of assumptions which now appear as mathematical manipulations [see "Reference" below, SVERDRUP and MUNK, 1946].

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THEORETICAL AND EMPIRICAL RELATIONS IN FORECASTING BREAKERS AND SURF

H. U. Sverdrup and W. H. Munk

(Contribution from the Scripps Institution of Oceanography, New Series, No. 301. This work represents results of research carried out for the Hydrographic Office and the Bureau of Ships of the Navy Department under contract with the University of California.)

Abstract--The relations are given which govern the transformation of waves in shallow water and upon which practical methods for forecasting breakers and surf have been based. For each relation the theoretical background is stated, together with a brief summary of empirical evidence. The discussion includes examples of the application of some of the relations.

Introduction--Methods of forecasting waves in deep water [see "References" at end of paper, SVERDRUP and MUNK, 1946] have found some direct application, as, for example, in the operation of aircraft carriers and refueling at sea. More important, however, has been the application towards the forecasting of breakers and surf.

There are two extreme cases. One is the case of a long low swell offshore, which may be almost hidden beneath a short chop. When the swell "feels" bottom, its energy becomes concentrated in narrow crests separated by long flat troughs. Just before breaking, these crests rise sharply from the water surface and are usually the most important factor in determining the character of the surf zone. For this case, where the surf is the result of swell, the changes are so marked that the prediction of surf conditions would be hopeless without a fair knowledge of the transformation of waves in shallow water.

The other extreme deals with surf caused by a local sea due to an onshore wind. In this case, the waves are already steep in deep water, where they occasionally break into white-caps, and their transformation, as they travel into shallow water, is much less marked.

In nature there is, of course, a gradual transition between these extreme cases, and the classification of any particular situation can best be characterized by the parameter H_0/L_0, that is, deep-water wave height over deep-water wave length, known as wave steepness in deep water. In order to cover the entire range of conditions, our effort has been to express certain changes, such as the ratio breaker height to deep-water wave height, as function of the deep-water steepness. Factors other than deep-water steepness, for example beach slope and texture or local wind conditions, also contribute towards the appearance of the surf zone. These are usually of secondary importance, and they are not included in this brief discussion.

Most of the important relationships were derived from theory, using field and laboratory observations as checks. Observations made in the past were so inadequate as to make a special program of field observations necessary. The observations were carried out by the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography, and supplemented by model studies at the Beach Erosion Board in Washington, D. C., and the Department of Engineering of the University of California. On the basis of theoretical work and these observations, a forecasting manual, "Breakers and Surf," was prepared and published by the Hydrographic Office [UNITED STATES NAVY, HYDROGRAPHIC OFFICE, 1944].

Wave velocity and length--More than 100 years ago, Stokes developed the theory giving wave velocity as function of wave period and depth for irrotational waves. His results have been checked by a large number of field and laboratory observations under widely different conditions and found to apply with remarkable accuracy. In Figure 1 theoretical values of wave velocity have been plotted against values observed along the Scripps Institution pier. The observations have been collected in groups to eliminate some of the observational errors. The agreement is good except for a slight tendency for the observed wave velocities to exceed the theoretical wave velocities. This discrepancy can be eliminated to a large extent if allowance is made in the theory for the height of the waves, but even without this correction the accuracy is sufficient for most practical purposes.

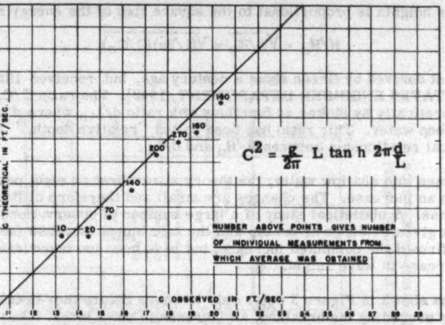

Fig. 1--Observed and theoretical wave velocities in shallow water according to observations along the pier at Scripps Institution of Oceanography, La Jolla, California

The theoretical values of the wave velocity in Figure 1 are computed from the classical equation

$$C^2 = (gL/2\pi) \tan h\, (2\pi d/L) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

According to equation (1), the wave velocity C decreases with decreasing depth d, but the change is appreciable only when the depth of water becomes less than half the wave length L. For that reason shallow water has been defined as water of depth less than a half wave length (see Fig. 2). From the time the wave enters shallow water until it breaks the wave velocity decreases, but the wave period remains unchanged. Therefore, as the waves pile into the shallow water, there is also a decrease in wave length. The wave height, however, increases as the wave train is being compressed, except for certain special cases which will be taken up later.

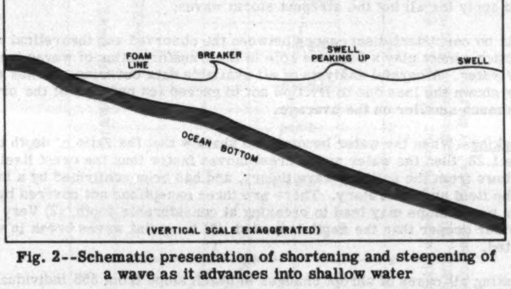

Fig. 2--Schematic presentation of shortening and steepening of a wave as it advances into shallow water

Wave height--The following discussion refers to changes in wave height for waves coming straight into shore without changing direction. Changes in wave height can be satisfactorily predicted from the law of conservation of energy:

$$(E_o/2)C_o = nEC \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In deep water one-half of the total energy, E_o, travels at the velocity C_o. In shallow water a fraction n of the energy E travels at a velocity C. The fraction n is sometimes used to express the relationship between the wave and group velocities. The ratio of the energies equals:

$$E/E_o = (1/2n)(C_o/C) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and the ratio of wave heights is proportional to the square root of the energy ratio:

$$H/H_0 = \sqrt{E/E_0} = \sqrt{(1/2n)(C/C_0)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Equation (4) was first derived by Green about a century ago, but received little attention until recently [UNITED STATES ENGINEER DEPARTMENT, 1942]. The ratio C/C_0 and n have both been expressed theoretically by Stokes as functions of a ratio d/L_0, where d is the depth and L_0 the wave length in deep water. This ratio has been called "relative depth." The line in Figure 3 gives the theoretical relationship between H/H_0 and d/L_0.

As the wave comes into shallow water, the theory shows first an eight per cent decrease in wave height and then an increase. The changes are small and therefore difficult to detect from individual observations. A statistical study of a large number of observations in the University of California wave tank gives evidence of the dip and the subsequent increase (see Fig. 3). Field observations have confirmed the computed increase, but have been too inaccurate to confirm or deny the small initial decrease in wave height.

The observations shown in Figure 3 refer only to waves before they break. During a short interval immediately preceding the breaking, an increase in wave height takes place which is more rapid than the one given by the Stokes theory. The reason for this discrepancy can be found in the rapid change in shape of the wave at that time, giving rise to a type of wave for which wave height is not proportional to the square root of the energy.

When the forecasting manual was written, it was necessary to rely entirely upon empirical relationships for forecasting the breaker height. Recently these empirical relationships have been brought into accordance with theory by treating waves near the point of breaking as solitary waves. The solitary wave consists ideally of a single crest extending an infinite distance on either side, and its motion is irrotational. The theory of solitary waves was developed by Stokes and Boussinesq for application to tidal bores and similar phenomena, but it has been found that it can be applied also to some studies of breaker characteristics.

One such application is shown in Figure 4. The curve gives the ratio of breaker height over deep water wave height as a function of the initial steepness (ratio: wave height to wave length in deep water). This relationship is derived from the solitary wave theory and the assumption that energy is conserved. The circles show observed values on Atlantic and Pacific beaches. Although individual observations deviate considerably from the theory, on the average the theoretical relationship seems to apply for all but the steepest storm waves.

Since there is no consistent discrepancy between the observed and theoretical values, one may conclude that friction cannot play a decisive role in the transformation of waves traveling from deep into shallow water. A careful analysis of all available data covering beaches of slopes from 1/20 to 1/100 has shown the loss due to friction not to exceed ten per cent of the original wave energy, and to be much smaller on the average.

Depth of breaking--When the water becomes so shallow that the ratio of depth to wave height reaches the value 1.28, then the water at the crest moves faster than the crest itself, and the wave breaks. This follows from the solitary wave theory, and has been confirmed by a large number of observations in the field and laboratory. There are three exceptions not covered by the theory: (1) Abrupt changes in beach slope may lead to breaking at considerable depth. (2) Very steep storm waves break in water deeper than the depth indicated. (3) Very flat waves break in water of smaller depth than indicated.

After eliminating all cases of abrupt changes in beach slope from 555 individual observations at various localities, the average observed ratio of depth over breaker height equals 1.27, as compared to the theoretical value of 1.28. Individual observations lie roughly between 1.1 and 1.5, and this deviation cannot be altogether ascribed to observational error. The result has been interpreted to indicate that the profiles of individual breakers differ; some are steeper, others less steep than the solitary wave. Some of the scatter in Figure 4 can also be related to this circumstance. But on the average the breakers seem to resemble the profile given by the solitary wave theory and follow the theoretical rules.

Wave refraction--The discussion so far refers to waves coming straight into a beach without change in direction. Waves approaching at an angle tend to turn parallel to shore, since the portion of the crest nearer shore is in shallower water and moves slowly while the crest in deeper water races ahead. The rate of turning can be computed according to Snell's law of refraction. In a few

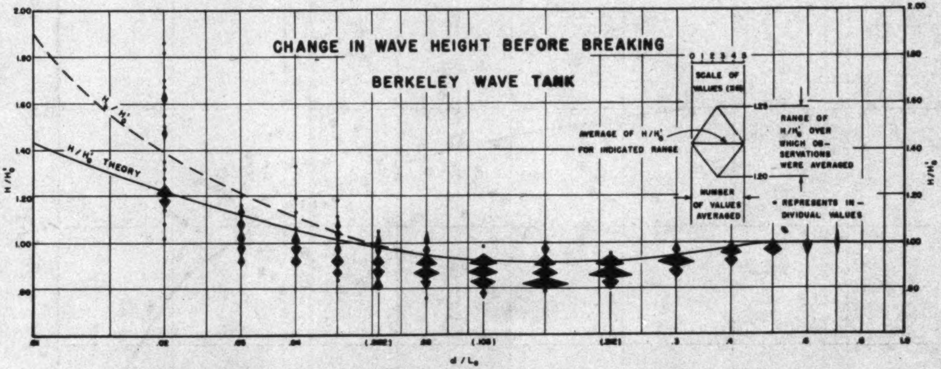

Fig. 3--Ratio wave height over deep-water wave height as function of relative depth. Line gives theoretical relationship, filled-in figures show distribution of observed values. Theory and observations both show initial decrease followed by increase

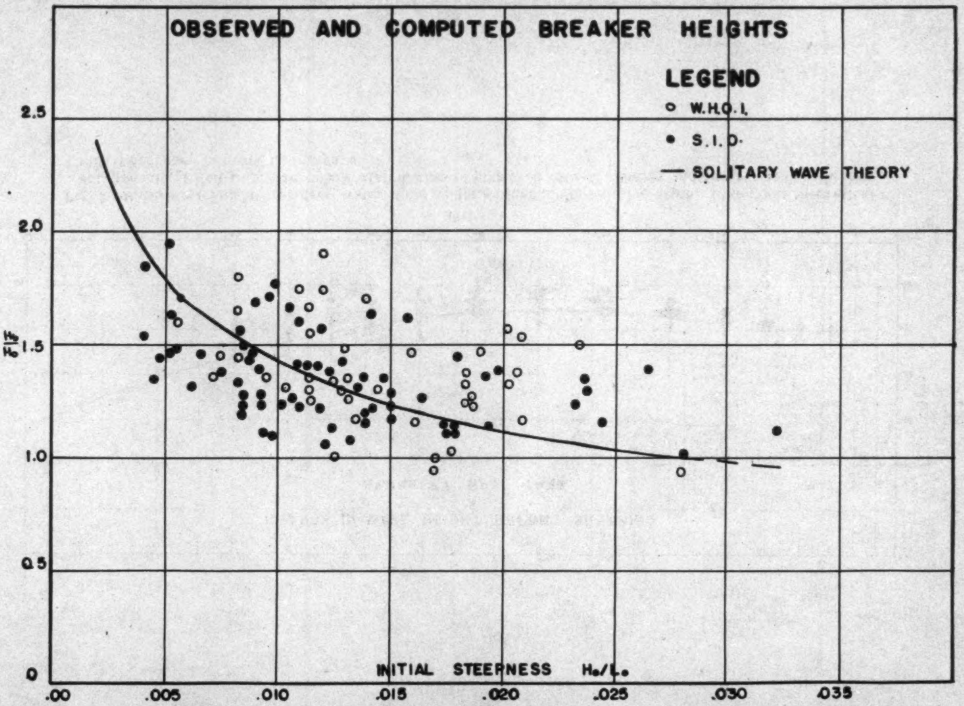

Fig. 4--Theoretical and observed ratio breaker height to deep-water wave height as function of initial steepness cases the computations have been checked by aerial photographs and found to provide good description of the phenomenon. Figure 5 shows an aerial photograph of a swell coming into shore north of Oceanside, California, on June 16, 1944. The swell came from the south-southwest. The position of the crests as shown on the aerial photograph is also indicated by the hatched lines in Figure 6. The computed positions are designated by solid lines. In general, the agreement is good. The application of Snell's law to regions of much more complicated bottom topography than the one at Oceanside has been equally successful.

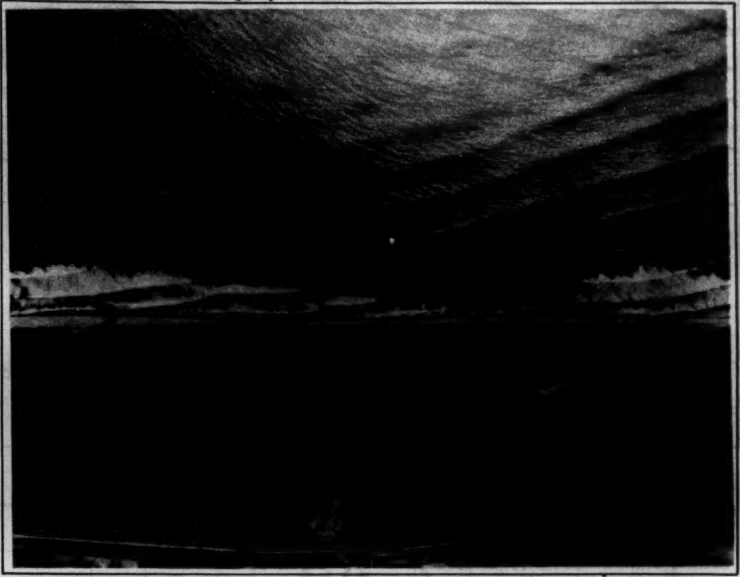

Fig. 5--Aerial photograph showing swell turning parallel to shore north of Oceanside, California

Convergence and divergence--Changes in wave direction also have an indirect effect upon wave height. This refraction factor must be considered in addition to other factors influencing wave heights. There is one important difference: While these other factors, which have been discussed earlier, depend only upon the wave characteristics in deep water and are therefore independent of the orientation of the coastline and the configuration of the bottom, the refraction factor depends solely upon these latter features and is therefore responsible for changes in wave height along a beach. The relative shelter behind headlands and the heavy surf on the exposed side of an island [ARTHUR, 1946] can all be explained in terms of the effect of refraction on wave height.

To compute this effect, it is necessary only to apply the law for the conservation of energy to a certain length of crest, bounded by two moving points A and B. Both points always travel normal to the direction of the wave crest, and the paths described by these points are called "orthogonals." If the waves approach a straight beach at an angle and the wave turns parallel to shore, the distance between A and B increases (the orthogonals diverge), and the energy must be distributed over a longer distance. This stretching causes the waves to decrease in height.

The effect is much more pronounced as waves bend into bays or around headlands and islands. A similar effect can be noted over submarine canyons. There the portion of the wave crests over the center of the canyon are in deeper water and move ahead faster than on either side and cause a bending outward from the center of the canyon which gives rise to low waves on the shore opposite the canyon. Underwater ridges, on the other hand, have the opposite effect. Waves over these ridges are in shallower water and are retarded, while on either side waves rush ahead and bend

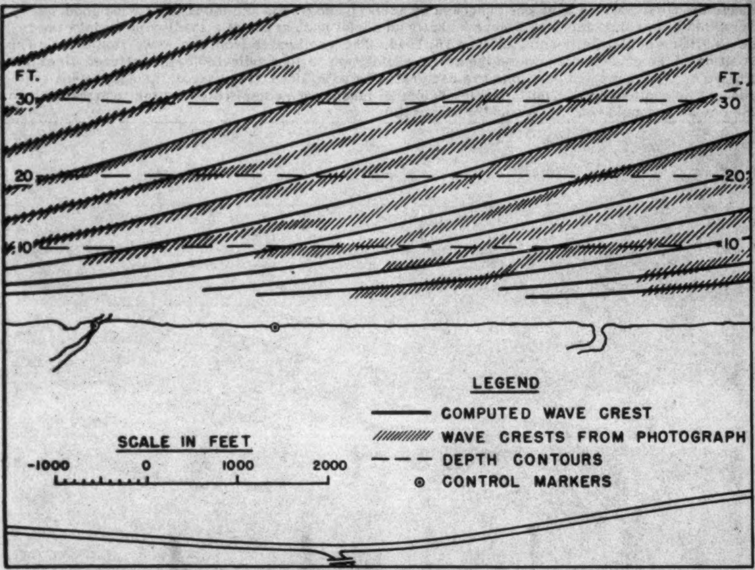
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Fig. 6--Comparison between observed position of wave crests shown in Figure 5 and positions computed according to Snell's law

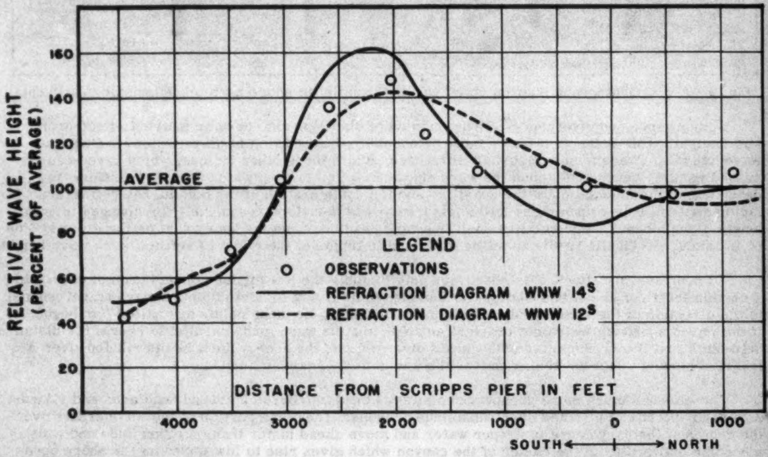

Fig. 7--The computed wave heights along Scripps Institution beach change by a factor of 3-1/2 to one, in accordance with the observed changes inward creating a convergence over the ridge. On the shore opposite underwater ridges waves will be higher than at either side.

The effect of these submarine features upon wave height can be very pronounced. Opposite the mouth of a submarine canyon 4000 ft south of the Scripps Institution pier at La Jolla, California, the waves are usually one-third as high as at the pier itself. A quantitative study of such variations caused by features of the bottom topography can be made by constructing a refraction diagram through a step-wise application of Snell's law. The position of the wave crests are computed and orthogonals, that is, lines which are everywhere normal to the wave crests, are then drawn. The changes in wave height along a beach can be computed from the convergences or divergences of these orthogonals.

The curve on Figure 7 shows the computed variation in wave height along the Scripps Institution beach for waves 12 and 14 sec in period from the west-northwest. The points represent the averages of many observations under similar conditions and are in general agreement with the computed values. This agreement indicates that the assumptions underlying the theory are basically sound: That wave refraction is the primary mechanism controlling changes in breaker height along a beach, and that friction, diffraction, and other processes can only be of secondary importance.

It may be interesting to note that refraction diagrams have been useful in planning amphibious operations during the War. Figure 8 shows a refraction diagram prepared for the Lingayen Gulf months before the invasion of the Philippines. The following quotation is taken from the Naval Aviation Confidential Bulletin, April 1945: "On the basis of this refraction diagram, the third amphibious force concluded that the best landing conditions would obtain over the eastern beaches between Dagupan and San Fabian . . . Military necessity dictated that the landings be conducted on the approximate center of the beach area near the town of Lingayen . . . After the first assault waves had been consolidated ashore, a northerly swell gradually increased and soon prevented further landing operations. Fortunately, these conditions did not persist so as to isolate the first waves ashore. At the same time, it is of great importance to note that during this entire period landing conditions remained good over those beaches originally selected as most available."

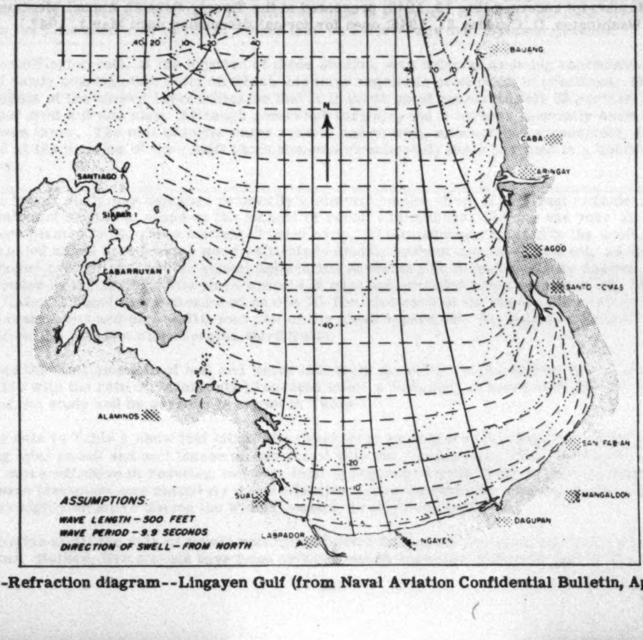

Fig. 8--Refraction diagram--Lingayen Gulf (from Naval Aviation Confidential Bulletin, April 1945)

Longshore currents and beach erosion--From a study of the relationships between breaker characteristics and longshore, or littoral, currents, a method has also been developed for predicting longshore currents. Ultimately, it should also be possible to learn enough about the processes of beach erosion due to wave action to forecast the formation of sandbars, or the manner in which a storm may alter the beach profile.

Conclusions

On the basis of the relationships discussed so far, a number of plates have been drawn, from which the characteristics of the breakers can be determined readily if the character of the waves in deep water has either been forecast or measured directly [UNITED STATES NAVY, HYDROGRAPHIC OFFICE, 1944]. The method of forecasting breakers and surf is based to a great extent, therefore, upon classical hydrodynamics, a field which seems to have fallen into disrepute during the last few decades. Although the assumptions underlying the classical equations are never completely fulfilled in nature, it is interesting to note that these equations have led to results which have found successful practical application.

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THE INFLUENCE OF TREATMENT AND SLOPE LENGTH ON RATE OF RUNOFF FROM COLLINGTON SANDY LOAM

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Abstract--In conjunction with the measurement of total soil and water losses from different soil treatments and slope lengths, data were also collected on rate of runoff from four plot areas. These included three 70-foot slope lengths consisting of untreated, annual cover crop, and annual manure treatments, and one 210-foot slope on an untreated area. Tabular data are presented for five representative storms showing maximum rates of precipitation and runoff, and the total periods of time during which rain fell and runoff occurred at rates exceeding 0.00, 0.25, 0.50, 1.00, and 2.00 in/hr.

The data indicate that: (1) The rate of runoff from any particular condition varies with rainfall intensity and with season. (2) Increased slope length under conditions of this study had no consistent effect on rate of runoff. (3) Soil organic matter additions either from cover crop or manure were effective in reducing runoff rate during the growing season. (4) The relative effectiveness of organic matter treatments decreased as rainfall intensity increased. (5) Winter cover crops, under certain conditions, may greatly increase runoff rate from winter storms. (6) Soil-moisture content at the beginning of the storm has much less influence of rate and amount of runoff from this sandy soil than is the case on many other soil areas.

Data were collected on rate of runoff from certain areas in conjunction with the measurement of runoff and soil losses from different soil treatments and slope lengths at the Marlboro Soil Conservation Experiment Station. Information on both rate and total amount of runoff is necessary for the best design of erosion-control structures. A structure having a small discharge capacity will handle a large volume of runoff if sufficient time is allowed. However, the capacity must be based on the maximum rate of runoff rather than on the average over a longer period.

The Collington soil, at the location of these studies, was selected as being representative of the light sandy coastal plain soils on which intensive vegetable production is practiced. Mechanical analysis of the plowed layer indicates that it is made up of approximately 83 per cent sand and 17 per cent silt and clay. Although somewhat variable, the B horizon is usually heavier than the surface layer. The soil absorbs water readily and is well, although not excessively, drained. The land at the location of the runoff plots slopes approximately three per cent in a southwesterly direction.

The runoff study was designed primarily to determine the effect of different organic-matter treatments and lengths of slope on the amount of runoff and soil loss. In any one year all of the plots were planted to the same cultivated truck crop. The treatments applied in the work reported here included check areas which were cultivated annually without special treatment, an annual winter cover crop of rye, and an annual application of manure at 20 tons per acre applied and plowed under in the spring. The plots were 14 ft wide and included slope lengths of 70, 140, and 210 ft. Rates of runoff were measured on one 70-foot plot each of the check, cover-crop, and manure treatments and on one 210-foot plot of the check treatment. No measurements of rate of runoff from the 140-foot slope lengths were made.

Since the total amounts of soil and water lost from the different treatments are of interest in connection with the rate of runoff data presented later, a summary of these data for the entire period of the study and by seasons is shown in Table 1.

The data in Table 1 show that either the cover-crop or manure treatment was effective in reducing total runoff and soil losses as compared with the check areas. The cover crop was relatively more effective in reducing soil loss than in reducing runoff. With respect to soil losses, the manure treatment was relatively more effective during the growing season, whereas the cover crop was highly effective during the winter season, as might be expected.

Analysis of all the rate of runoff records collected during the period of the study will not be presented. Rather, five storms have been selected which represent different typical conditions.

Descriptive data on soil conditions, storm characteristics, and runoff for each of these records are shown in Tables 2 to 6, inclusive.

Table 1--Total runoff and soil losses[a] from check, cover crop, and manure treatments on the Marlboro runoff plots, June 1938 through December 1941

Treatment and period	Precipitation	Runoff	Soil loss
	in	in	tons/acre
Entire period	163.43		
Check		14.34	19.76
Cover crop		12.30	11.42
Manure, 20 tons/acre		8.98	12.31
Growing seasons, Apr. 1 to Nov. 1	110.89		
Check		10.67	15.47
Cover crop		8.35	10.90
Manure, 20 tons/acre		6.30	8.91
Winter seasons, Nov. 1 to Apr. 1	52.54		
Check		3.67	4.29
Cover crop		3.95	0.52
Manure, 20 tons/acre		2.68	3.40

[a] Each datum on runoff and soil loss represents the average value for the treatment indicated from two plots 70 ft, two plots 140 ft, and two plots 210 ft in length. All plots were cropped to carrots followed by beets in 1938, tomatoes in 1939, sweet corn in 1940, and peas followed by cabbage in 1941.

Table 2 shows a winter storm of average intensity, the soil not frozen. The soil surface was bare on check, manure, and long slope plots, and there was rye five inches tall on the cover-crop plot. The storm lasted for 12 hr and 49 min, during which time there were 1.64 inches of precipitation. The maximum intensity of precipitation was 1.80 in/hr for a four-minute period.

Table 2--Storm of January 14-15, 1940

Treatment	Slope length	Runoff	
		Amount	Maximum intensity
	ft	in	in/hr
Check	70	0.29	1.58 for one min
Cover crop	70	0.02	0.40 for one min
Manure	70	0.09	1.06 for one min
Check	210	0.29	0.80 for two min

Table 3 shows a winter storm of average intensity, the soil partly frozen. The soil surface was bare on check, manure, and long slope plots, and there was rye six inches tall on cover-crop plots. The storm lasted for 12 hr and 51 min; there were 1.70 inches of precipitation; and the maximum intensity of precipitation was 0.93 in/hr for an 11-minute period.

Table 3--Storm of February 7, 1941

Treatment	Slope length	Runoff	
		Amount	Maximum intensity
	ft	in	in/hr
Check	70	0.09	0.44 for one min
Cover crop	70	1.55	0.73 for two min
Manure	70	0.02	0.14 for two min
Check	210	0.10	0.43 for one min

Runoff for the storm of February 7, 1941, includes the effect of the snow that was on the cover-crop plot at the start of the storm. The snow had melted from the check and manure plots before the rain started. This situation is common during winter and early spring and, for that reason, the record is included here. Frost in the soil under a cover crop thaws more slowly than on bare areas. Frequently the soil is frozen under a cover crop and unfrozen on adjacent bare plots at the time of a storm. When this occurs the runoff from cover cropped areas is high but the soil loss is ordinarily negligible.

Table 4 shows a summer storm of average intensity with dry soil. The crop was sweet corn two to three inches tall. The duration of the storm was six hr and 45 min, during which time there were 1.87 inches of precipitation with a maximum intensity of 2.10 in/hr for a two-minute period.

Table 4--Storm of May 30-31, 1940

Treatment	Slope length	Runoff	
		Amount	Maximum intensity
	ft	in	in/hr
Check	70	1.01	1.28 for one min
Cover crop	70	0.54	0.69 for two min
Manure	70	0.26	0.69 for one min
Check	210	0.85	1.14 for one min

Table 5 shows a summer storm of high intensity with moist soil. The crop was cabbage plants set on July 3. The storm lasted four hr and two min, and there were two inches of precipitation with a maximum intensity of 3.60 in/hr for a two-minute period.

Table 5--Storm of July 7, 1941

Treatment	Slope length	Runoff	
		Amount	Maximum intensity
	ft	in	in/hr
Check	70	1.04	2.74 for two min
Cover crop	70	0.92	2.57 for four min
Manure	70	0.80	2.61 for one min
Check	210	0.88	1.96 for six min

Table 6 shows a summer storm of high intensity with wet soil. The crop was cabbage plants set on July 3. The duration of the storm was one hr and 44 min, and the amount of precipitation was 1.40 in. The maximum intensity of precipitation was 3.60 in/hr for a one-minute period.

Table 6--Storm of July 8, 1941

Treatment	Slope length	Runoff	
		Amount	Maximum intensity
	ft	in	in/hr
Check	70	0.82	3.00 for one min
Cover crop	70	0.82	2.74 for one min
Manure	70	0.78	2.74 for one min
Check	210	0.81	2.58 for one min

Data on rates of runoff are of value in determining accumulated amounts only when the time or duration of each rate is known. In the following tabulations, corresponding with Tables 2 through 6, the total number of minutes when rainfall and runoff exceeded certain specified intensities is shown. P = rainfall, and R = runoff.

Table 7--Storm of January 14-15, 1940

Treatment	Slope length	Intensity in in/hr									
		0.00		0.25		0.50		1.00		2.00	
		P	R	P	R	P	R	P	R	P	R
	ft										
Check	70	757	133	59	23	30	5	4	1	0	0
Cover crop	70	757	8	59	2	30	0	4	0	0	0
Manure	70	757	49	59	5	30	3	4	1	0	0
Check	210	757	195	59	13	30	6	4	0	0	0

Table 8--Storm of February 7, 1941

Treatment	Slope length	Intensity in in/hr									
		0.00		0.25		0.50		1.00		2.00	
		P	R	P	R	P	R	P	R	P	R
	ft										
Check	70	765	41	143	11	11	0	0	0	0	0
Cover crop	70	765	712	143	78	11	12	0	0	0	0
Manure	70	765	19	143	0	11	0	0	0	0	0
Check	210	765	103	143	11	11	0	0	0	0	0

Table 9--Storm of May 30-31, 1940

Treatment	Slope length	Intensity in in/hr									
		0.00		0.25		0.50		1.00		2.00	
		P	R	P	R	P	R	P	R	P	R
	ft										
Check	70	405	193	152	90	85	58	26	6	2	0
Cover crop	70	405	128	152	57	85	20	26	0	2	0
Manure	70	405	124	152	16	85	4	26	0	2	0
Check	210	405	193	152	90	85	44	26	3	2	0

Table 10--Storm of July 7, 1941

Treatment	Slope length	Intensity in in/hr									
		0.00		0.25		0.50		1.00		2.00	
		P	R	P	R	P	R	P	R	P	R
	ft										
Check	70	238	75	73	47	41	36	34	28	26	10
Cover crop	70	238	78	73	43	41	34	34	23	26	6
Manure	70	238	58	73	36	41	26	34	22	26	7
Check	210	238	99	73	52	41	37	34	23	26	0

Table 11--Storm of July 8, 1941

Treatment	Slope length	Intensity in in/hr									
		0.00		0.25		0.50		1.00		2.00	
		P	R	P	R	P	R	P	R	P	R
	ft										
Check	70	90	78	70	47	58	30	29	19	17	6
Cover crop	70	90	77	70	46	58	33	29	17	17	6
Manure	70	90	70	70	38	58	24	29	18	17	8
Check	210	90	104	70	45	58	34	29	17	17	4

The total periods of time shown above represent the actual periods during which rain fell or runoff occurred. Whenever there was one min or more during the record when rainfall or runoff stopped, that time was not included in the above tabulations. The apparent discrepancy between the reported duration of storm and total minutes above 0.00 intensity is due to this procedure. It should also be noted that the periods of time when runoff exceeded some specified intensity do not necessarily represent a continuous period but may be the summation of two or more shorter periods.

The data shown in Tables 2 to 6 can be used to compute values of C in the rational equation as outlined by RAMSER [see "References" at end of paper, 1927]. The maximum rates of rainfall and runoff, when shown for periods of more than one min, represent true maxima for a one-minute period. In the case of the precipitation for the storm of February 7, for example, the maximum intensity attained was 0.93 in/hr, which rate was maintained for an eleven-minute period.

Summary

It has been shown by experimental work at the Marlboro Station [KNOBLAUCH, KOLODNY, and BRILL, 1942; NEAL, 1943; NEAL, 1944] and at other locations that cover crops and organic matter additions to the soil reduce runoff and erosion losses. The present study was designed to study the effect of such treatments and the effect of slope length on the rate of runoff during storm periods. Knowledge of runoff rate is essential for satisfactory design of terraces and other erosion-control structures.

Data are presented for five representative records, giving characteristics of the storms and the amount and maximum rate of runoff from the different treatments. A summarization of the total periods of time during which rain fell and runoff occurred at rates exceeding 0.00, 0.25, 0.50, 1.00, and 2.00 in/hr is also shown for each record.

The two slope lengths under comparison were 70 ft and 210 ft. Under the conditions that obtained in this study, there was no consistent difference in either the amount or maximum rate of runoff from these two slope lengths. This outcome is not in agreement with results from laboratory studies [IZZARD, 1944] and numerous field studies that have been conducted in other areas. The reason for this divergence of results is not clear as yet. It may be related to the fact that the soil at the location of the work reported here is very sandy and the land slope considerably more gentle than at the location of most other field studies on slope length.

It should be noted that these results concern only the length of slope under conditions where lateral movement of runoff water is prevented. They are not representative of watershed areas where increased lengths of slope afford opportunity for concentration of water from side areas as well as from up-slope areas. Under the latter situation, increased lengths of slope on unprotected fields in the coastal plain area usually result in increased quantities of runoff and consequent erosion damage.

Comparisons were also made of differences in rate of runoff from areas that had an annual winter cover crop of rye, areas receiving 20 tons per acre of manure annually before plowing, and from untreated areas.

The rate of runoff from any particular treatment varies with the intensity of rainfall and with the season. Observations throughout the course of the study indicated that the manure treatment was most effective in the spring and early summer months following the application. The cover crop, except when the soil was frozen, was most effective during the winter period, but continued to exert a marked influence on rate and amount of runoff after the crop was plowed under.

During storms of low to moderate intensity, either the cover crop or the manure treatment was effective in reducing the maximum rate of runoff as compared with that from check areas. During storms of high intensity, however, there was a relative decrease in differences in rates of runoff from the different treatments. This condition is evident in the data for the storms of July 7 and July 8, 1941. Differences in the maximum intensity of runoff from the various treatments were considerably less during these relatively high intensity storms than with storms of lower intensity.

Data on the influence of soil moisture on rates of infiltration and consequent reductions in runoff are available in the records of the two July storms. At the beginning of the July 7 storm the soil was moist as a result of rain on July 3 and 4. Moisture conditions were favorable for plant growth, but the soil was not wet. At the beginning of the July 8 storm, however, there had been 2.44 in of rain during the preceding 24-hour period. The two rains causing runoff were fairly similar with respect to maximum intensity and total periods of time during which certain intensities prevailed. Crop conditions were essentially identical, of course, since only a 24-hour period had elapsed. The two records thus provide a comparison of the influence of soil-moisture level on runoff. The peak rates of runoff reached during the July 8 storm on wet soil are slightly higher for all conditions on the short slope and considerably higher on the long slope. However, the data in Tables 10 and 11 show that the total periods of time during which rates of runoff exceeded the indicated intensities are rather similar for the two storms. Added moisture is known to move downward readily in this soil until the surface layers are reduced to field capacity. The present data indicate that soil-moisture level has much less influence on rate and amount of runoff from this soil than in many other soil areas.

It has been pointed out elsewhere [COPELY et al, 1944; LAMB, FREE, and WILSON, 1944] that storms of high intensity rather than of large amount are responsible for a major portion of annual soil and water losses. A summary of rainfall intensities at the Marlboro location during the period from 1938 through 1944 shows a total of 54 storms during which a five-minute intensity exceeded two in/hr. Of these, 51 occurred during the season from April through October, whereas only three occurred from November through March. It is thus evident that the erosive storms occur largely during the growing season. The seasonal occurrence of erosive storms is a fact of primary importance in the planning and application of conservation measures on cultivated land in the coastal plain area.

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ASSIGNMENT OF FREQUENCIES TO A COMPLETELY ORDERED SET OF SAMPLE DATA

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Abstract--It is pointed out that the problem of reaching an optimum fit of a cumulative frequency curve by analytical methods does not involve directly the assignment of either individual confidence intervals or individual frequencies to the observed values of the sample.

When one tests the nature of the function used to describe the behavior of the universe from which the sample be drawn, or the randomness of the observed sample, there may arise the occasion for the assignment of individual confidence intervals to each sample value. The assignment of a best reference point (such as a best frequency value) within a confidence interval, such as the mean, median, or mode, is shown to be subordinate to that of the assignment of a confidence interval.

If, for purposes of graphical fitting, it is found desirable to assign a frequency to each sample value, the writer, in general, recommends the mean frequency of the mth ordered observation:

$$\hat{F}_m = m/(n + 1)$$

In certain cases it may be possible to estimate frequencies of the mth values by

$$\hat{F}_m = F[E(x_m)]$$

independently of the unknown parameters, and such points might prove more desirable to use for graphical fitting near the extremes, if errors along the x direction are balanced out visually, relative to these points.

Nature of the problem--In this paper an attempt will be made to clarify certain confusion of thought which has arisen relative to the "assignment of frequencies" to a completely ordered set of sample values.

Let x_i, i = 1, 2, . . . n, denote a random set of n values of x drawn from a universe whose probability density function is f(x). Let these be ordered so that

$$x_i \leq x_{i+1}, \quad i = 1 \text{ to } n - 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Let F(x) denote the cumulative distribution function

$$F(x) = \int_{-\infty}^{x} f(s)ds \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The assumption is made that F(x) involves one or more unknown parameters. The determination of values for these unknown parameters is a standard problem of statistical estimation [see "References" at end of paper, WILKS, 1943]. When possible, "sufficient" statistics of the sample should be used in making such estimates. Also it is desirable to use the "sufficient set of statistics" which yields the most precise or "efficient" estimate [WILKS, 1943; KIMBALL, 1946].

If sufficient statistics are used in such estimate, and it is possible to characterize the probability distribution of these statistics, it will be possible to estimate the range of error to be expected in the fitted curve, relative to the information furnished by the observed data. This procedure, denoted by Problem A, will solve the problem of forecasting or extrapolation from the fitted curve, provided that the form of the function fitted expresses the true behavior of the universe from which the data are drawn.

Thus to solve completely the problem of forecasting, there must also be a test to determine how well the universe is characterized by the mathematical function chosen to fit data drawn from that universe. This will be denoted as Problem B. For example, in the problem of forecasting the behavior of annual maximum flood flows, on a probability basis, the universe referred to above is thought of as the series of all flood flows in the particular locality investigated. The annual maxima observed constitute a sample of all annual maxima. Thus the reliability of forecast will involve testing whether the observed data series can be explained as a random sample from a universe presupposed to behave like the mathematical function fitted. At the present time the author is working on a testing procedure which he believes is particularly suited for testing the fit of a frequency curve to completely ordered sample values.

In a broad sense the estimation of the parameters (Problem A) does not involve assignment of frequencies to observed data but rather furnishes an estimate of the complete frequency function--under a subjective assertion as to the form of function that should be used. It is when one wishes to test the validity of the above assertion (Problem B) that it may be found necessary to assign frequencies to observed data.

In general, there may be said to be two approaches to such a test in a completely ordered series of sample data. They are: (1) How well do the frequencies predicted from the fitted frequency curve agree with the individual frequencies of the sample values? and (2) How well do the values of x observed in the sample agree with the expected values of x in a completely ordered series of this size drawn from a universe characterized by the fitted mathematical function?

In the first method the frequency predicted from the curve, at $x = x_m$, is determinant. The question as to what frequency should be assigned to the sample value for purposes of comparison is open. In the second method the sample value x_m is determinant, and the question is open as to what value of x the fitted curve points to, as a proper norm for comparison with the sample value x_m.

Testing the fit of the frequencies of the fitted curve relative to the frequencies expected from the sample values (Problem B, first method)--Let fitted cumulative frequency curve be denoted by G(x) and its derivative by g(x). From the general theory of the "mth value" [GUMBEL, 1943] the probability distribution of the mth value x_m in terms of the true cumulative frequency F(x) and its derivative f(x) is given by

$$(n/m)mF^{(m-1)}x_m[1 - F(x_m)]^{(n-m)}f(x_m)dx \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

This can be regarded as the probability distribution of the true cumulative distribution function at the mth ordered value x_m. Denoting $F(x_m)$ by F_m for brevity, it would then be written as

$$(n/m)mF_m{}^{(m-1)}[1 - F_m]^{(n-m)}dF_m \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where F_m may vary only between limits zero and unity. Knowledge of this distribution enables one to set up a confidence interval for each ordered value (m = 1, 2, . . . n). For example, from (4) it follows that the mean value of $F_m = E(F_m) = m/(n + 1)$, and the variance of $F_m = \sigma^2(F_m) = [1/(n + 2)]E(F_m)[1 - E(F_m)]$.

Although the distribution (4) departs from normal character near the extremes, that is, for m near 1 or near n, it is of normal character near the median, $m = (n + 1)/2$. It is of simple enough character, however, so that it is theoretically possible to set up precise confidence intervals for F_m for each ordered value, with confidence coefficients 0.90, 0.95, and 0.99, for example. Thus a test for Problem B would be the behavior of the fitted function G(x) relative to this set of confidence intervals, that is, the test would be whether $G(x_m)$ for each value of m, was in the corresponding confidence interval based upon the true cumulative distribution F(x) for the mth ordered value.

It will be noted that in such a test a confidence interval is assigned to each mth value, rather than a single value $\hat{F}(x_m)$.

In plotting the observations relative to the fitted curve, or in setting up an analytical testing procedure, it will be necessary to assign a single value $\hat{F}(x_m)$ for each observation. It is important to note that such a plotting or reference points in themselves do not offer a satisfactory testing procedure. For a test of fit one must also know the confidence intervals corresponding to each observation, that is, the standard error and approximate form of error distribution. Otherwise one is testing on a basis of a situation where the probability of being right is infinitesimal in relation to the probability of being wrong (since the probability that a set of observations corresponds exactly to a set of best reference points is infinitesimal), even though the reference points are taken as those which most probably correspond to the observations, for example, the maximum likelihood choice of reference points which involves using the modal values [GUMBEL, 1943].

If for plotting purposes one wishes to denote a single value $\hat{F}(x_m)$ as a best value, one is immediately confronted with several possible choices, none of which would affect the rationale of the above test, that is, such a choice would not affect the definition of the confidence interval, which depends entirely upon the complete distribution (4) and the confidence coefficient chosen. The writer would prefer to use the mean value $m/(n + 1)$ as the point of reference for plotting purposes. In the first place, deviations from the mean have a statistical significance which is of common knowledge. Furthermore, such a choice of reference point is, from the statistical point of view, ipso facto, unbiased, and in graphical fitting, tends to give an unbiased result, providing no distortion of scale is involved due to use of special type of graph paper.

One example will be given to illustrate this last point. Suppose data were being fitted in a case where there was reason to believe that the true cumulative distribution function was of the form $F(x) = cx$, $f(x) = c$, c = an unknown constant, with the lower limit of x known to be zero and the upper limit unknown (at $x = 1/c$). If the modal value of F_m were used as reference point, then from (3) it would follow that $\hat{F}_m = (m - 1)/(n - 1)$. In order to make the illustration more concrete, suppose that the x axis is taken as horizontal and the F axis as vertical. Thus at the extremes $m = 1$ and $m = n$, $\hat{F}_1 = 0$, $\hat{F}_n = 1$. Since these are the limits of the cumulative frequency distribution function, it follows that the confidence interval at $m = 1$ lies entirely above (and including) the reference point $\hat{F}_1$, and at $m = n$ it lies entirely below (and including) the point $\hat{F}_n$. Obviously this is not a proper situation for purposes of graphical fitting. The effect would be to draw the ends of the fitted curve $G(x)$ too near to zero at x_1, and too near to one at x_n.

If the mean were used rather than the mode no bias in the fitting procedure would result (either in the technical or nontechnical sense of the word "bias").

The test of fit which the writer is working on would involve the squares of the deviations of $G(x_m)$ from its expected value $E(F_m) = m/(n + 1)$, $m = 1, 2, \ldots n$. Perhaps for this reason the writer is especially inclined to favor the use of $\hat{F}_m = E(F_m) = m/(n + 1)$ as a reference point for plotting. What can be said objectively is that Problem B with the first method involves essentially a confidence interval for each value of m, irrespective of what reference point $\hat{F}_m$ is plotted.

Testing of fit of observed values x_m relative to corresponding mth values indicated by fitted frequency curve--Now in the graphical picture, we have taken the F axis vertical and the x axis horizontal. Thus the confidence intervals referred to in Section 2 are a set of intervals on the vertical lines through the observed values of x, x_m, $m = 1, 2, \ldots n$.

In the second method the confidence intervals must be set up along horizontal lines for each mth value. In this case whether or not $G(x_m)$ lies on the confidence interval for the mth value depends entirely upon whether the abscissa of $G(x_m)$, which is x_m, lies within the horizontal confidence range or not.

The problem of estimating the confidence range of x at the mth value is more complicated than that of estimating the range of $F(x_m)$, since the length of range is measured in terms of x, and hence in using the distribution (3) the form of the functions $F(x)$ and $f(x)$ comes into play. Also the parameter values would have to be used to determine completely the confidence range. This would mean that a fitted function $G(x)$ would be used in determining the confidence range of the mth value of x.

Thus the graphical representation of the confidence intervals would be intervals indicated on horizontal lines drawn through the points $F = G(x_m)$, $m = 1, 2, \ldots n$ (where curve $G(x)$ crosses vertical lines through x_m).

If any reference point is needed on such a confidence range, the writer would prefer to use the mean value of the mth value of x as obtained from (3) for reasons similar to those outlined for choosing reference points on the vertical confidence intervals. The use of the modal value of x as the reference point is open to the same criticism brought out in the preceding section.

If an analytical test for the randomness of the observed sample relative to the fitted function were set up involving deviations of x_m from values pointed to by the fitted function (that is, horizontal deviations, in contradistinction to vertical deviations treated in the last section), the writer believes that these deviations should be measured from the mean values of x_m, $m = 1, 2, \ldots n$, as determined from (3).

Thus, if reference points are to be plotted, he favors the points $\hat{x}_m = E(x_m)$.

It might be mentioned that for certain types of functions it is possible to determine $G[E(x_m)]$ independently of the values of the unknown parameters in $G(x)$. For example, for the distribution of

maximum values [GUMBEL, 1943], such points are not too difficult to determine near the upper extreme of the total range of x, that is, for confidence intervals with index m near n. Thus for purposes of graphical fitting such points could be determined on the vertical lines through x_m, without knowing the parameters. However, if this is done, it should be borne in mind that in making the graphical fit near such points, horizontal errors should be balanced out visually rather than vertical errors.

Comparison of the two approaches to Problem B--A comparison of the two approaches to testing closeness of fit of the function G(x) to the observed sample values x_m may be roughly outlined as follows:

First method (confidence ranges in the F direction)--Here the distribution of the true frequency function F_m of the mth ordered value is given by (4), and thus confidence intervals can be determined for any value of n (size of sample) and m, independently of what type of function is used in fitting the curve. The fitted frequency values $G(x_m)$ are then compared with these confidence intervals, or with points $\bar{F}_m$ on those intervals.

Second method (confidence ranges in the x direction)--Here the confidence intervals have to be determined from the fitted function G(x). The observed sample values x_m are then tested with reference to these confidence intervals, or with reference to their deviations from some point such as $E(x_m)$ which involves knowledge of the function fitted.

It would appear that certain features of the first method make it more desirable than the second. It is simpler to apply, and comparisons are with intervals or points which do not involve the function fitted, while in the second method the confidence intervals involve the function fitted, and in many cases are complicated to compute.

However, for certain portions of the curve (usually the extreme portions), a test involving horizontal confidence intervals would be more sensitive than one involving vertical confidence intervals. Thus for functions that are not too complicated, the second method might be used to supplement the first.

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THE PLACE OF ELECTRICAL SOIL-MOISTURE METERS IN HYDROLOGIC RESEARCH

E. A. Colman

Abstract--Many kinds of hydrologic research can be facilitated by the use of direct-reading, electrical soil-moisture meters. These meters can be used to measure accretions and losses of soil moisture and the direction and rate of soil-water movement; they can provide a means of controlling the time and amount of irrigation on crop land; and they can discern freezing and melting conditions of water in soil and snow.

These uses require that the soil unit of the meter be small, rigid, and resistant to corrosion and deterioration. The moisture-absorbing dielectric through which the measurement is made must be thin enough and completely enough exposed to the soil to eliminate any significant time lag in moisture indication. The measuring unit must be rugged, portable, and self-contained, for field use.

A meter has been developed by the United States Forest Service to meet these specifications.

Introduction--Progress in hydrologic research depends, in large part, upon the development of methods and tools by which it can be prosecuted economically in terms both of time and effort. Hydrologic research is inherently time-consuming because of its dependence upon the whims of the weather and the generally unpredictable nature of seasonal rainfall distribution. In the past it has been effort-consuming to a discouraging degree because of the lack of uniformity of soil, rock, topography, and vegetation, even over small areas. The purpose of this paper is to point out the possibility of reducing the effort involved in certain phases of hydrologic research by the use of an electrical measuring device. The measuring device to be discussed is a soil-moisture meter which is intended to provide an efficient means of indicating the amount of water held at any moment within a block of field soil and the direction and rate of movement of that water. The possibilities of its use, however, are considerably broader.

Incentive for the development of an electrical method of measuring field soil-moisture content arose from the desire to reduce the large amount of labor involved in the sampling, weighing, and drying operations incident to its direct measurement, and the impossibility of obtaining successive measures at the same spot. Early efforts toward electrical measurement involved burying two electrodes in the soil and measuring the electrical resistance between them [see "References" at end of paper, GARDNER, 1897]. This method was found to be unsatisfactory upon the discovery that the contact resistance between soil and electrodes was variable and contributed a considerable portion of the total measured resistance. The four-electrode method of McCORKLE [1931] eliminated contact resistance by a mathematical device but met with only limited success because of uncertainty as to the path followed by the electric current in the soil, which left some question as to which part of the soil block was being measured.

In the more promising moisture meters the electrical measurement has been made within a porous dielectric block, the moisture content of which varies with the moisture content of the soil in which it is buried. The block moisture content determines its heat conductivity or its electrical resistance or capacitance. This type of device, including those developed by SHAW and BAVER [1940], BOUYOUCOS [1940], FLETCHER [1939], and ANDERSON [1942], has been much more satisfactory than the earlier types because of the stability of the measuring medium and the predictable nature of the contact resistance between electrodes and dielectric. Some problems in this method still remain to be solved, but they have been narrowed down to choice of the proper dielectric material and methods of calibration.

General specifications for an electrical soil-moisture meter

A soil-moisture meter must possess certain characteristics of material and design if its usefulness is to be as broad as possible. The meter comprises two parts: The soil unit which is buried in the soil and changes its electrical properties in response to soil moisture changes, and the meter unit with which these electrical properties are measured.

The soil unit must be rigid enough to permit its burial in the soil without deformation. It must be small enough so that its presence will not affect soil-water movement, even when a number of units are placed in a single soil block in relatively close proximity. The base, absorbing dielectric, and electrodes, must be made of inert materials which will not deteriorate under the influence of soil solution, roots, or organisms, during the period of use. The dielectric block must be sufficiently thin and well enough exposed to the soil so that its moisture content will show no appreciable time lag behind moisture changes in the soil around it. Its electrical properties must be susceptible of simple and rapid measurement.

The meter unit must be rugged, completely self-contained, small enough to be readily portable, and capable of precise measurement over a wide range of soil moisture. For greatest facility in use it should be a direct-reading, rather than a balancing, type of meter, and its operation should be as simple as possible.

An instrument that meets these specifications has been developed on the San Dimas Experimental Forest of the United States Forest Service. It has been subjected to a number of tests that have shown it to be stable over long periods of exposure in the soil, capable of rapid measurement,

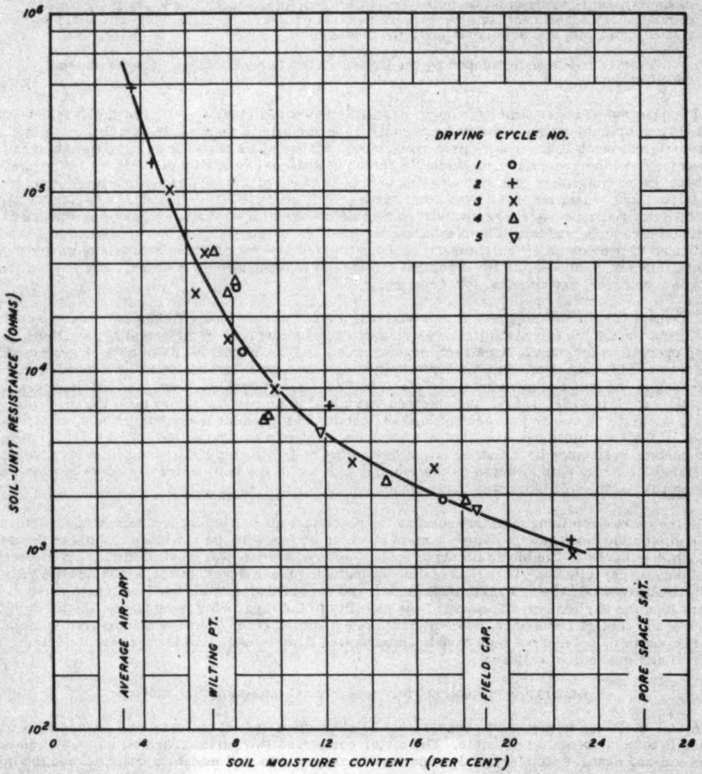

Fig. 1--Relation between soil-moisture content and soil-unit resistance in a field plot

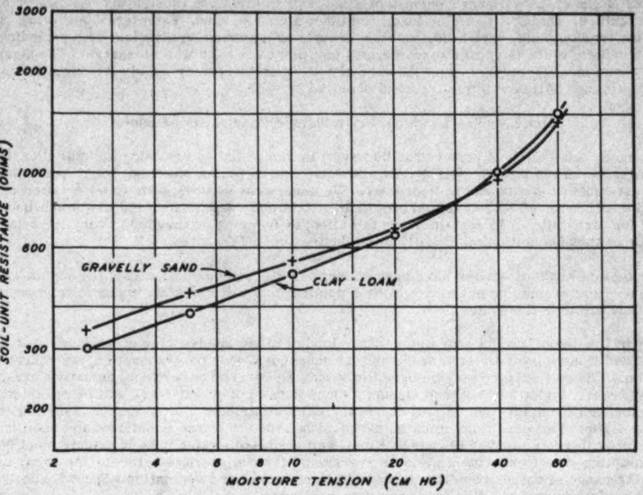

Fig. 2--Relation between moisture tension and soil-unit resistance in two texturally different soils

and consistent in its electrical characteristics. Tests are being continued in the field and laboratory.

The soil unit of this instrument is a disk-shaped, methacrylate-type plastic base, upon which are mounted two monel screen electrodes separated by several layers of Fiberglas fabric. The Fiberglas serves as the porous dielectric. Imbedded in the rim of the disk is a coil of 50 ft of fine copper wire which serves as a resistance thermometer. The temperature measurement is necessary in order to obtain the most precise measurement of soil-moisture content.

The soil units are designed to be buried either singly in the soil or in groups, mounted in line on a metal staff. When mounted in the latter fashion they can be spaced along the staff as desired, the lead wires of each unit lying along the staff on the side opposite to that on which the units are exposed, and the whole assembly packed into an auger hole dug in the soil. Connection with the meter is made through a multiple pole switch at the soil surface.

The meter unit is an alternating-current ohmmeter and is used to measure the alternating-current resistance between the electrodes of the soil unit. The meter is entirely self-contained. A battery-operated vacuum tube oscillator generates low-frequency alternating current which passes between the electrodes. The measuring current is rectified by a selenium oxide bridge-type rectifier and its magnitude indicated on the dial of a microammeter. Operation consists merely in zeroizing the meter, pressing the switch, and reading the microammeter dial. Dial readings are directly related to resistance.

The temperature measurement is made with a separate circuit in the same meter designed specifically to measure small differences in resistance over a limited range.

The curves presented in Figures 1 and 2 illustrate typical relationships determined by means of the moisture instrument just described. In Figure 1 are shown electrical resistance and soil-moisture data obtained in a plot of uniform soil which was alternately irrigated and dried over a period of seven months. Periodic measurements of soil-unit resistance and soil-moisture content were made during this time. It will be noted that (1) there is no shift in the calibration curve through the period of study, (2) there is no break in the curve either at high or low moistures, and (3) the soil unit gives promise of being useful for measurements of moisture well in excess of the field capacity.

Figure 2 shows the uniform response of a soil unit to moisture tension in two soils which differ widely in texture. One soil is a clay loam, the other a coarse sand. Samples of both were laid on a porous clay tension plate, saturated, and then brought to moisture equilibrium with periodically increased tensions, while the resistance of a soil unit placed in each was measured. The significant result of these measurements is that the data of both soils trace very nearly the same curve. The fuller significance of this will be discussed shortly.

Some studies in which soil-moisture meters can be useful

Electrical soil-moisture meters can be useful in many studies involving the status or disposition of water in porous media. Soil is only a special kind of porous medium, but it happens to be one of great concern to students of hydrology. We must know what happens to water after it has entered the soil, what effect is exerted upon it by plants and evaporation, and how much becomes available for streamflow. In certain cases the effect of freezing or thawing is very important and a detection of these conditions is greatly to be desired.

Four typical kinds of studies have been chosen for discussion to illustrate the way in which soil-moisture meters can be put to use. Other applications will certainly occur to workers in fields less familiar to the writer.

Study of the disposition of soil water--This kind of study involves the measurement of rate and amount of additions to soil-water storage and its subsequent loss by evaporation, transpiration, and percolation. The soil surface may be bare, or it may be covered with crops, or native grasses, shrubs, or trees. Under any of these circumstances it is certain that there will be considerable variation through the study area in soil characteristics, distribution of roots, and completeness of vegetative cover. Two conditions must be satisfied in order to obtain consistent and significant measures of soil-water storage changes. First, sufficient soil-water measurements must be made at each sampling time to provide a reliable average soil-water storage value for the area, or to measure the range of values resulting from variations in soil and vegetation. Second, successive individual measurements must be made in close proximity.

The foregoing statement indicates the necessity for intensive moisture sampling in such a study. A single set of samples taken at each sampling date will not suffice. Electrical soil-moisture meters can provide a welcome alternative to the enormous physical effort involved in making such a study by the conventional method of auger sampling and laboratory moisture analysis of the soil samples. The soil units of these meters are small, they provide an indication of soil-moisture content at the point of installation, and their measurement can be accomplished simply, rapidly, and at any time required. The units can be buried at any depth in the soil, and as many can be installed throughout the study area as is necessary to determine a significant average measurement or to establish the range of moistures within the plot. The only significant problem facing the worker is that of relating the electrical measurement of the units to soil-moisture content. This can be done most directly by taking soil-moisture samples close to each unit in sufficient number to cover the moisture range to which that particular soil is subject. Such a procedure involves some labor and may be disappointing to those who foresee in the use of a moisture meter the possibility of throwing away their soil augers. However, at present it seems the surest method of calibration will probably be required until a more satisfactory method has been developed. Even including the necessity for field calibration of the moisture meters, however, a study of soil-water disposition making use of them would be far simpler and more reliable than one requiring periodic manual sampling of the soil.

Study of the direction and rate of soil-water movement--It has been shown elsewhere [BODMAN and EDLEFSEN, 1934] that soil moisture moves in response to gradients of gravity (gravitational potential) and soil-moisture tension (pressure potential). Its rate is determined by the magnitude of the algebraic sum of those two gradients in any direction and by the permeability of the soil to water or its vapor. The general equation relating these functions (Darcy's equation) states that the rate of movement is directly proportional to the total potential gradient between two points in the soil and the average soil permeability between them.

Periodic soil-moisture sampling alone cannot always indicate the direction or rate of soil-moisture movement in the field, because there may be external additions to or losses from the measured soil block. It is necessary to supplement moisture measurements with measures of soil-moisture tension so that the direction of movement can be established. If the direction of movement is known, then the source of soil-moisture additions or losses can be determined. Tensiometers have been used for this purpose [MOORE, 1939, and NEAL, RICHARDS, and RUSSELL, 1937], but they are inherently useful only in the high-moisture range and they require frequent and careful attention.

Electrical soil-moisture instruments making use of a porous dielectric are well suited to this type of study, because the moisture content of the dielectric, and hence its electrical response, depends primarily upon the moisture tension of the soil surrounding it. It is possible, for example, to calibrate such instruments directly against moisture tension and to obtain very similar calibration curves for soils differing widely in texture. Differences between the curves are due to differences in electrolyte concentration in the several soil solutions.

The requirements of a field study of soil-water movement will indicate the usefulness of soil-moisture instruments for this purpose. Measurements of soil-moisture tension must be made nearly simultaneously throughout a three-dimensional grid of positions within the soil block so that the directions of water movement at the several soil levels can be determined. Periodic measurements of soil-moisture content at these positions will indicate the magnitude of moisture changes there. A minimum of disturbance is required within the soil block to avoid having the method of study affect the subject of the study. This, of course, makes it undesirable to sample the soil moisture frequently with an auger or tube.

It is proposed that electrical soil-moisture instruments be utilized for such a study in the following way. Auger holes are drilled into the soil block at the locations at which moistures and tensions are to be measured. (The soil units of the moisture instruments will later be placed at the desired depths within these holes.) Samples of soil from the desired depths can be used in the laboratory to establish the relationship between the electric characteristics of the soil units to be buried there and soil-moisture tension. In soils lacking a well-defined field structure it is possible that laboratory study can also be used to relate the soil-unit measurement to soil-moisture content. Then, when calibrated in terms of tension and moisture, each soil unit is buried at its proper position in the field soil block. The field portion of the study thereafter requires merely the periodic measurement of the electrical status of the soil units and the conversion of each measurement into moisture tension and moisture content. If the soil is such that the units cannot be calibrated in terms of moisture content in the laboratory, then, as was mentioned earlier, a series of field-moisture samplings must be made to cover the moisture range to which the soil block is subject.

In some instances the moisture content at two points in the soil may remain constant while the tension measurements indicate the existence of a moisture-moving force toward one of them. This means that water is moving through the soil without raising or lowering its water content. In this steady-state condition the rate of movement can be determined only if the permeability, as well as the total potential gradient, is known. Soil permeability, which is the rate of water flow under unit total potential gradient, decreases as soil-moisture content decreases, and is rather difficult to measure precisely. A satisfactory approximation, however, can be obtained from measurements of water movement and total potential gradients made in the soil block during periods when small soil-moisture accretions and losses between two points can be measured. This determination will not be precise because tensions at the two points will also be changing and the precise application of Darcy's equation requires a steady-state condition. The success of the approximation arises from the fact, well illustrated by MOORE [1939], that permeability decreases very rapidly in the soil-moisture range between saturation and field capacity, having at the latter point a value about one per cent of that at saturation. Comparatively large errors of measurement, therefore, will not seriously invalidate the determination.

Control of irrigation on cropland--Time and amount of irrigation have generally been determined by rule of thumb methods. This often results either in waste of water and fertilizer elements by over-irrigation, or damage to crops through the use of too little water. Rule of thumb methods are developed only after long experience with known crops in known locations, and the introduction of new crops or the opening of new locations does not always permit the immediate use of previously acquired irrigation techniques. A method of irrigation control is needed that will permit the direct determination, on the spot, of the time when irrigation is required and the amount of water that should be applied.

The irrigation-control problem can be approached most logically by using the crops themselves as the indicators of water requirements. Several studies have been made of the growth of plants in relation to soil-moisture content [VEIHMEYER, 1932], and in general they have shown that most crop plants are not adversely affected by water shortages until the soil-moisture content in the root zone drops to values rather close to the wilting point. This establishes the wilting point as a very important soil characteristic and as one basic reference point for irrigation control. A second reference point is the field capacity of the soil. This is the maximum amount of moisture that can be retained in the soil against the force of gravity. The irrigator must work with water stored in the soil between these values. His need is for some instrument that will indicate when the soil has approached sufficiently close to the minimum moisture and when, during irrigation, it has reached the maximum.

Electrical soil-moisture instruments can be used for irrigation control if they are designed to respond promptly to changes in soil-moisture content. It was stated earlier that the porous dielectric type of soil unit provides very similar calibration curves relating its electrical characteristics to soil-moisture tension over a wide range of soils. This means that at the wilting point, corresponding to a moisture tension of about 15 atmospheres in most soils, the moisture instrument should yield a nearly constant measurement regardless of the soil in which it is placed [JOHNSTON, 1942]. Therefore, if a soil-moisture unit is buried within the root zone of a crop it should be a simple matter to determine when the soil there is in need of irrigation.

The indication of field capacity depends upon the fact that as irrigation water penetrates the soil each soil layer is raised to a moisture content somewhat greater than this value before water passes through it to moisten the next one beneath [VEIHMEYER, 1932]. The problem becomes considerably simpler in this case. When irrigation water has reached a certain depth it is known that between there and the surface the soil has at least reached its field-capacity moisture content.

The problem of irrigation control, then, can be solved by placing soil-moisture units at the maximum soil depth at which plant water supply is critical. Frequent periodic measurements made upon these units will indicate the time when irrigation is required. Measurements made during irrigation will indicate when sufficient water has been applied, that is, when water has penetrated to the depth of the units.

No great precision is required in making these measurements, because of the large differences in electrical response of the moisture instruments between field capacity and wilting point. As an example of this BOUYOUCOS [1940] shows that his plaster of Paris soil units have an electrical resistance of 500 ohms at about field capacity and 60,000 ohms at the wilting point. Other porous dielectrics show similarly great ranges. Furthermore, the rate of resistance change in these materials per unit change in soil moisture becomes greater as the soil moisture decreases, so that even small changes in moisture near the critical wilting point can be measured readily.

The location of the moisture units in the soil will, of course, depend upon the root distribution of the crop being studied. The same depth of burial cannot be used for all crops and all soils, as has been shown by SCOFIELD [1945]. The proper depth can be determined either from previous knowledge of crop root habits or by using soil units buried at a number of depths, determining the critical depth by measurements during the first irrigation cycle.

Detection of freezing and melting of water--Knowledge of the presence of ice layers in the soil and the depth to which the soil is frozen are important in certain kinds of hydrologic investigations. It is also sometimes important to know whether the snow pack lying on the soil is melting or freezing or whether all its water occurs as ice crystals. These determinations cannot always be made by the use of thermometers. In snow both water and ice or either one can be present at the same temperature. This is also true in soil, but here the problem is further complicated by the fact that, at low moisture contents, soil water freezes only at temperatures considerably below 32°F.

Electrical soil-moisture instruments can be used to detect freezing and melting because of the very great difference in resistivity between the liquid and solid phases of water. If soil units are placed either in soil or snow there will be sudden and great changes in their resistance values as some or all of the water held in the units changes from one phase to the other. Although no field measurements of this kind have been made by the writer as yet, the possibilities of use of electrical soil-moisture instruments for this kind of study are highly intriguing.

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DISCUSSION

Waldo E. Smith (American Geophysical Union, October 30, 1946)--From the description of the soil-moisture meter presented in this paper, it appears that the author has found the solution to a problem that has long plagued soil physicists. Many soil-moisture meters have been developed, based on various principles, but all, to the writer's knowledge, have had fundamental defects, such as limited range of moisture evaluation, requiring frequent calibration, delicateness of installation, or a combination of difficulties.

A rugged instrument, not requiring frequent adjustment or recalibration, that will measure moisture content over the full range of field conditions will be the open-sesame to many hitherto knotty hydrologic problems both in the research and the applied fields. The author has outlined its use in three such problems, namely; the study of soil-moisture movement, the evaluation of irrigation requirements, and the study of moisture conditions under a snow-covered or frozen surface. All of these, as he points out, require the evaluation of a calibration curve similar to his Figure 1. Once such a curve has been established, only occasional additional check values would need to be secured, and if the instrument is so rugged that a single installation might last, say, ten years or longer, this should not prove serious. It could be compared to the stream-flow measurement work done at a stream-gaging station with stable control to check the stability of the station's rating curve.

One further step should be taken in this connection that would prove most useful in irrigation work and at the same time extend the usefulness of the instrument to many flood-control problems. This is to reduce the per cent of moisture value to a quantitative basis, for example, inches depth of water per inch depth of soil. Then on irrigated lands one might compute definitely the number of inches of water required to bring the soil in the root zone from a given value up to field capacity.

In flood-control problems dealing with saturated-ground conditions, such as those of the winter floods of the Ohio Valley, a series of batteries of such soil-moisture meters would give operating engineers definite knowledge of the ability of the soil to infiltrate and hold more water. A battery would consist of a series of meters in a given location at various depths of the soil mantle, so that the inches of depth of water in the mantle at any time could be determined. Knowing, from previous occasions, the ultimate limit of the soil moisture, the additional holding capacity of the mantle could be established at the point. A series of such locations at properly selected points would establish a value for the watershed. The determination of moisture movements under a snow-covered or frozen surface and the movement of the frost line are also of great importance in certain flood-control problems.

If the instrument described in this paper is of such rugged construction as to meet operational requirements, it should indeed have a great field of usefulness. It should be given thorough consideration.

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NOTES ON DETERMINING THE EFFECTIVE DISTANCE TO A LINE OF RECHARGE

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Introduction--Increasing emphasis has been given in recent years to the installation of wells in sand and gravel deposits along perennial streams. Under favorable conditions water enters the aquifer from the adjacent stream so that the safe yield is not limited by recharge from local precipitation [see "References" at end of paper, JEFFORDS, 1946]. Some of the installations tested, however, have not been successful. At times the preliminary investigations have been inadequate, and often quantitative hydrologic techniques have been applied without adequate consideration of the existing local conditions.

The approximate determination of the distance from a pumped well to the effective line of recharge constitutes a fundamental part of all these investigations. Experience has shown, moreover, that serious errors arise when general assumptions are made as to this distance, such as the distance from the production well to the bank of the stream or mid-line of the channel, rather than the effective distance from the production well to the line of recharge. It is the purpose of this paper to describe a method for the calculation of the effective distance to the line of recharge from pumping-test data and to show how the method is applied to data collected in the field. This technique was suggested to the author by C. E. Jacob in May, 1945, and supplements a slightly different method of approach devised by the writer in 1943 for a similar purpose.

Theory--The basic equation for relating the drawdown in an observation well with pumpage, time, distances, and the physical constants of a limitless, homogeneous, isotropic aquifer having a large thickness is given by

$$s = Q/4\pi T[-\mathrm{Ei}(-r^2S/4Tt)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where s = drawdown of the piezometric surface of a well discharging at a uniform rate Q, r = distance from discharging well to point where the drawdown is measured, S = coefficient of storage of aquifer, t = time the well has been discharging, and T = coefficient of transmissibility of the aquifer.

A line of recharge to an aquifer in the vicinity of a discharging well may, in accordance with the theory of groundwater hydrology, be replaced for mathematical treatment by an equivalent recharging image well on the opposite side of the line of recharge and at a distance equal to the distance between the original well and the line of recharge (see Fig. 1).

The drawdown at the observation well may then be represented by the algebraic sum of the drawdowns caused by the real well and image well. As the image well represents a source of recharge, its effect is negative, so that the drawdown is decreased,

$$s_o = s_r - s_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where s_o is the total drawdown at the observation well, s_r is the drawdown at the observation well caused by the real well, and s_i is the drawdown at the observation well caused by the image well.

Referring all symbols to Figure 1

$$s_o = Q/4\pi T[-\mathrm{Ei}(-b^2S/4Tt)] - Q/4\pi T\left\{-\mathrm{Ei}[-(2a-b)^2S/4Tt]\right\} \quad \ldots\ldots\ldots (3)$$

If we let $Q/4\pi T$ and $S/4T$ equal unity, then at any time t

$$s_o = -\mathrm{Ei}(-b^2/t) - \left\{-\mathrm{Ei}[-(2a-b)^2/t]\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

rewriting equation (4)

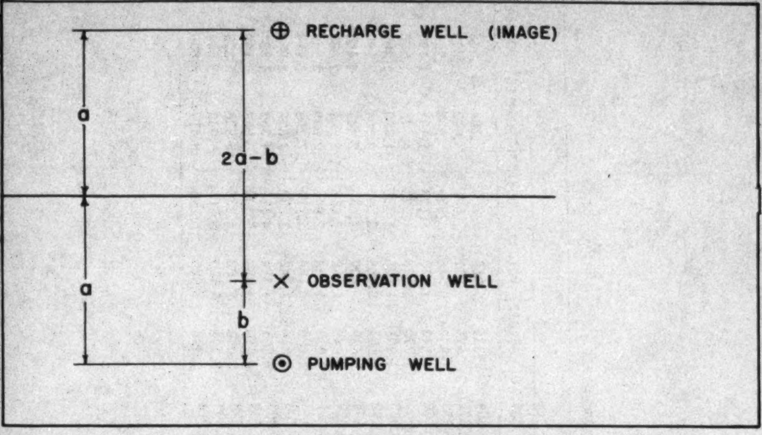


Fig. 1--The relationship between the pumped well, observation well, image well, and the line of recharge

$$s_o = - Ei(- b^2/t) - [- Ei(- Nb^2/t)] \quad (4a)$$

then

$$Nb^2 = (2a - b)^2 \quad (5)$$

$$N = 4a^2/b^2 - 4a/b + 1 \quad (6)$$

and

$$a/b = 1/2 \pm \sqrt{N}/4 \quad (7)$$

It is then possible to compute values of s_o for different values of a/b.

Table 1 gives values of u, a/b, and $[\Sigma - Ei(- u)]$. From values given, a family of "type curves" may be drawn, each member of which shows the effect of a particular ratio of a/b. When the observation well is located between the discharging well and the river, the positive values of the radical are used. When the observation well is on the landward side of the discharging well, the negative values are used. This family of type curves is used in a manner similar to the use of the $[- Ei(- u)]$ type curve described by THEIS [1935] and WENZEL [1942].

The observed drawdowns in each well, corrected for river fluctuations and possible barometric effects, are plotted on log paper, similar to that used for the type curves, against values of 1/t. The two graphs are superimposed and are moved with axes parallel until the curve plotted from the observed data most nearly coincides with one of the family of type curves. The ratio a/b of this type curve then can be used with the actual distance b between the discharging well and the observation well to determine the effective distance to the line of recharge.

The transmissibility and storage coefficients are determined from the observations of water-level change immediately after the beginning of pumping using the Theis graphical method.

Method of testing--A proposed well-field location should be selected, in a preliminary way, on the basis of already known facts relating to the geology of the area. For example, if the sands and gravels are known to be of small thickness and irregular extent, the site is a questionable one despite other considerations such as accessibility and the economics of a pipe line from the area.

When a proposed area seems favorable, a pilot well is drilled at the site of the proposed permanent well and one or more observation wells are drilled between the pilot well and the river. The pilot well then is pumped at a constant rate, and water levels in the observation wells are measured at periodic intervals. These measurements are facilitated greatly if an automatic water-

Table 1--Type-curve values for different values of a/b

Values of a/b	Values of u															
	1.647	.8237	.4118	.1647	.1029	.08237	.04118	.01647	.01029	.008237	.004118	.001647	.001029	.0008237	.0004118	.0001647
1.1	.051	.129	.222	.300	.322	.330	.348	.357	.361	.361	.364	.364	.364	.363	.364	.365
1.2	.070	.204	.376	.533	.581	.598	.634	.657	.663	.665	.671	.671	.671	.671	.672	.673
1.3	.077	.249	.482	.717	.793	.821	.868	.914	.924	.927	.935	.937	.938	.938	.938	.939
1.4	.079	.272	.554	.864	.968	1.006	1.087	1.139	1.152	1.159	1.168	1.172	1.173	1.173	1.174	1.175
1.6	.080	.286	.635	1.073	1.235	1.295	1.428	1.515	1.538	1.544	1.563	1.570	1.573	1.573	1.575	1.576
1.8	.080	.290	.665	1.203	1.420	1.504	1.691	1.818	1.853	1.864	1.889	1.901	1.905	1.906	1.909	1.909
2.0	.080	.291	.678	1.282	1.548	1.654	1.899	2.070	2.118	2.132	2.166	2.184	2.189	2.190	2.194	2.195
2.2	.080	.291	.681	1.329	1.636	1.763	2.083	2.282	2.344	2.365	2.406	2.430	2.437	2.439	2.443	2.445
2.4	.080	.291	.683	1.356	1.695	1.839	2.194	2.461	2.538	2.562	2.617	2.648	2.656	2.658	2.664	2.667
2.7	.080	.291	.683	1.371	1.748	1.913	2.341	2.684	2.784	2.818	2.891	2.933	2.944	2.948	2.949	2.960
3.0	.080	.291	.683	1.382	1.774	1.955	2.444	2.862	2.988	3.031	3.125	3.180	3.194	3.199	3.209	3.213
4.0	.080	.291	.683	1.385	1.796	1.996	2.604	3.238	3.455	3.534	3.706	3.814	3.843	3.852	3.872	3.884
5.0	.080	.291	.683	1.385	1.797	2.000	2.644	3.409	3.717	3.839	4.093	4.265	4.314	4.329	4.362	4.381
6.0	.080	.291	.683	1.385	1.797	2.000	2.653	3.527	3.941	4.114	4.547	4.876	4.969	5.000	5.067	5.108
7.0	.080	.291	.683	1.385	1.797	2.000	2.653	3.540	3.978	4.116	4.672	5.079	5.198	5.239	5.326	5.379
10	.080	.291	.683	1.385	1.797	2.000	2.653	3.545	4.005	4.215	4.805	5.374	5.550	5.613	5.746	5.830
14	.080	.291	.683	1.385	1.797	2.000	2.653	3.545	4.010	4.230	4.913	5.698	6.026	6.146	6.417	6.600

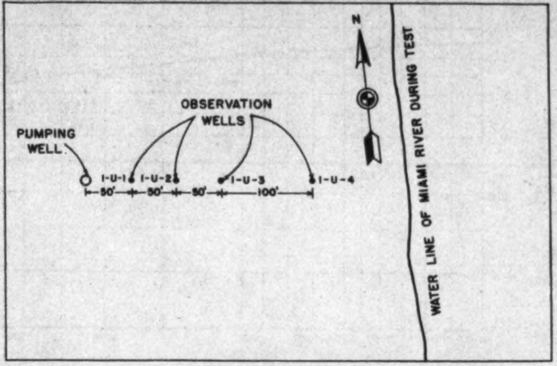


Fig. 2--Location of pumping well, observation wells, and river for pumping test in Miami Valley, south of Hamilton, Ohio

level recorder is installed on each observation well. After pumping starts, water levels are read from the recorder charts at ten-second intervals for the first few minutes, and the interval between readings is increased as the pumping test continues.

The transmissibility of the formation is computed by means of the Theis graphical method from data obtained in the first few minutes of the pumping test before the recharge from the river affects water levels in the observation wells. The factor a/b is determined by matching the family of type curves with data obtained from a longer period of pumping.

Application of method in the Miami Valley--In 1943, the writer obtained some data during a pumping test in the Miami Valley, south of Hamilton, Ohio, which illustrate this method of deter-

Table 2--Data obtained during a pumping test, discharge started at 12^{h}20^{m}, March 8, 1943

Date	Well 1-U-1		Well 1-U-2		Well 1-U-3		Well 1-U-4	
	Time	Drawdown	Time	Drawdown	Time	Drawdown	Time	Drawdown
	h m	ft	h m	ft	h m	ft	h m	ft
March 8	10 50	0.00	10 55	0.00	11 00	0.00	11 05	0.00
	14 11	1.70	14 15	1.05	14 18	0.67	14 33	0.56
	15 15	1.92	15 17	1.20	15 20	0.78	15 25	0.68
	16 12	1.83	16 15	1.12	16 18	0.85	16 25	0.72
	17 13	2.10	17 15	1.41	17 17	0.98	17 19	0.77
	18 08	2.16	18 05	1.47	18 07	1.02	18 07	0.82
	19 06	2.24	19 07	1.52	19 10	1.09	19 11	0.85
	20 11	2.31	20 15	1.58	20 20	1.14	20 21	0.87
	22 05	2.30	22 09	1.64	22 13	1.21	22 17	0.92
March 9	12 04	2.44	12 08	1.68	12 11	1.24	12 12	0.96
	04 06	2.49	04 08	1.78	02 12	1.27	02 13	1.01
	06 02	2.51	06 06	1.80	04 10	1.31	04 11	1.05
	08 00	2.55	08 01	1.85	08 03	1.37	06 10	1.08
	10 13	2.60	10 16	1.89	10 20	1.42	08 06	1.15
	14 03	2.63	14 11	1.91	14 13	1.45	14 15	1.17
	16 06	2.60	19 44	1.97	19 45	1.49	18 00	1.17
	19 42	2.67						
March 10	04 17	2.67					04 21	1.24
	16 10	2.71						

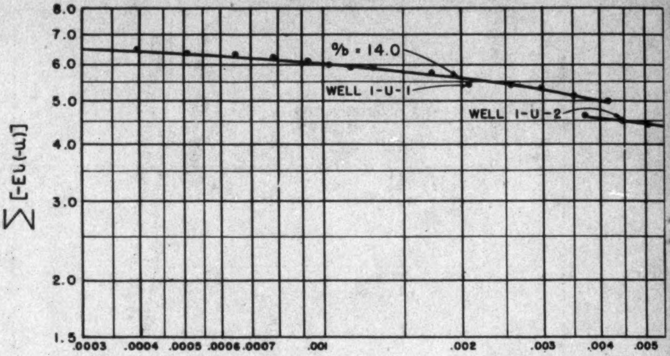


Fig. 3--Illustration of the way plotted points fall closely on various type

mining the effective distance from a pumping well to a source of recharge. The location of the river, pumping well, and the observation wells are shown on Figure 2. The area in back of the well corresponds to the postulates of the original derivation quite well, as it extends for about a mile. The river is practically straight for about 800 ft adjacent to the well. The aquifer is glacial outwash of sand and gravel about 135 ft thick and the river bottom is composed of loose gravel the size of eggs or larger.

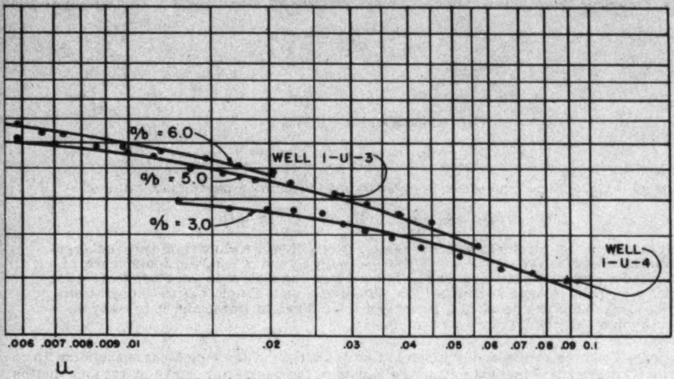
Data obtained from the test are given in Table 2. The discharging well was pumped for 55 hr; the temperature of the pumped water varied from 54°F to 56°F, and the pumping rate averaged 1700 gal/min as measured by a nine-inch Parshall flume equipped with an automatic recorder. Figure 3 illustrates the way the plotted points fit on the selected type curve when the points are "matched." The effective distance from the pumping well to the line of recharge is computed to be from 600 to 750 ft from the pumped well.

Summary--The technique which is described in this paper and applied to data collected under field conditions indicates the effective distance to the line of recharge in terms of two measurable variables, the drawdowns in a single observation well and the duration of pumpage. Of course, the distance from the pumped well to the observation well must be known, the observation well must be located approximately on a line between the pumped well and the line of recharge, the discharge rate of the pumped well must remain constant throughout the test, and the drawdown must be small compared with the thickness of the aquifer.

Unless the source of recharge affects the observation well and pumping well during the course of the test, the stream may not be a significant factor in insuring a perennial supply of groundwater. However, the judgment of the hydrologist conducting the investigation is very important both in determining the duration of the test and interpreting the results. The method described in this paper is not intended to be substituted for the experience and mature consideration of the investigator.

By means of a derivation similar to that described in this paper, it is possible to compute type curves for the effect of a fault instead of a river on drawdowns in a pumping well and an observation well.

Acknowledgments--Acknowledgment is made to George K. Mauney and James C. Matthai of the United States Geological Survey for their assistance in computing values of the type curves, and to Eunice Springer for preparing the graphs and illustrations. The method was developed during groundwater studies conducted under the general supervision of O. E. Meinzer, United States Geological Survey. The criticisms and comments of R. M. Jeffords and other members of the United States Geological Survey have been very helpful.



curves, enabling the effective distance to the line of recharge to be computed

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THE BACKWATER CURVE

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Abstract--A graphical procedure is given to aid in finding a particular value of

$$\eta = dy/dx = [S_o - (V^2/C^2R)]/[I - (V^2/gy_m)]$$

If all the values of η referring to the same rate of flow are plotted on two rectangular coordinate axes OX, OY where $X = (I/C^2R) - (\eta/gy_m)$ and $Y = S_o - \eta$, each rate of flow will yield a curve with two branches. For a given channel, it is very convenient for interpolating purpose to have at hand all the values of η on a graph, before integration. Finally, as V, η, and y are constants, lines appear as straight lines, and it is easy to obtain all the new values of η for a new value of S_o.

Introduction--A simple procedure is given to find the length of the reach corresponding to given depths by (1) a graphical method to find the slopes of the backwater curve at various depths and (2) known ways to find the integral of a curve when it is determined by equidistant ordinates.

The differential equation for steady gradually varied flow in a prismatic channel [see "References" at end of paper, ROUSE, 1938] is

$$dy/dx = [S_o - (V^2/C^2R)]/[1 - (V^2/gy_m)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

As the second member is easy to evaluate as a function of y, taking y as abscissa and x as ordinate:

$$dx/dy = [1 - (V^2/gy_m)]/[S_o - (V^2/C^2R)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Integration between two limits A and B will give the increment Δx corresponding to a given increment Δy [WOODWARD and POSEY, 1941]:

$$\Delta_A{}^B x = x_B - x_A = \int_A^B f(y)dy \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

We shall hereafter develop a graphical procedure to aid in finding particular values of dx/dy, which is the reciprocal of the integrand in equation (3).

If in equation (1) we put $dy/dx = \eta$, $1/C^2R = b$, we obtain

$$S_o - \eta = V^2(b - \eta/gy_m) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Now, if we plot on two rectangular coordinate axes as abscissa $X = b - \eta/gy_m$ and as ordinate $Y = S_o - \eta$, the curves η = constant, V = constant, and y_m = constant (or y = constant) will appear as straight lines. Their characteristics are given below.

Table 1--Characteristics of curves η = constant, V = constant, and y_m = constant

Equation		Slope	Intersection with		
			OX	OY	$Y = S_o$
η = constant,	$\eta = S_o - y$	0	$Y = S_o - \eta$	$X = \infty$	$X = \infty$
V = constant,	$Y/X = V^2$	V^2	0	0	S_o/V^2
y = constant,	$X = b - (S_o - Y)/gy_m$	gy_m	$b - S_o/gy_m$	$S_o - bgy_m$	b

The lines of equal discharge can also be plotted in the same coordinate axes, their equation is Q = VA where A is the area of the cross-section.

Each point of the f(y) curve in equation (3) is determined by two of the five variables X, Y, η, V, and y.

Construction of the diagram (see Fig. 1)--To determine the value of η corresponding to a particular value of y at a depth of, say, ten ft, y_{10}, first compute the corresponding values of $1/C^2R$ and gy_m.

Now construct the quadrilateral OSYQ, where the angle at S is 90°, $OS = S_o$, $SY = 1/C^2R$; QY is labelled y_{10} and is laid off through Y with the slope gy_m; OQ is a V line and is laid off through O with the slope V^2, where V is the velocity corresponding to the given discharge, say 20 cfs. Point Q, intersection of the y line and the V line, is labelled Q_{20}.

The vertical distance QP of point Q to the horizontal SY is the desired value of $\eta = dy/dx$ corresponding to y_{10} and Q_{20}. This can also easily be proved from the geometry of the Figure. η is positive when point Q is beneath SY and negative when above SY. Various y lines corresponding to the various values of y can be added and the points Q_{20} connected by a curve. If the discharge is changed a new Q-curve is required. If the bottom slope S_o changes, point S must be raised or lowered accordingly, and the y lines will not change if the values of $SY = b = 1/C^2R$ are taken from a Bazin or a Manning formula.

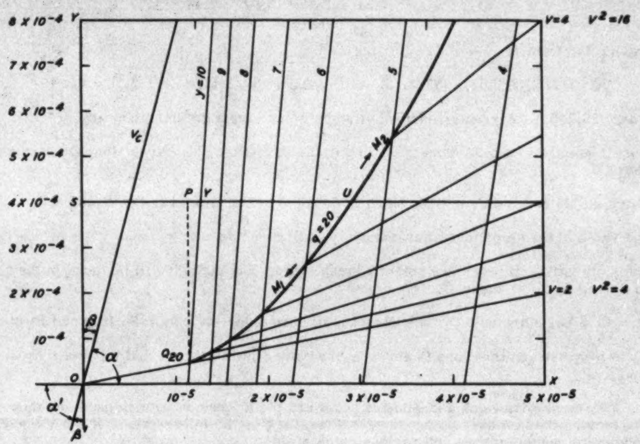

Fig. 1--Constant Q curve

The value of y at which a Q-curve crosses SY gives $\eta = dy/dx = o$. In other words, it is the normal depth for the particular values of Q and S_o (point U, Figure 1). Each Q curve has a common point at infinity with a y line, y_c, and a corresponding V line, in other words, at the critical depth.

Having thus found the various values of η in the interval AB, we can now plot the $1/\eta = dx/dy$ curve and integrate it within the limits A, B. $\Delta x = \mu_m \Delta y$ where μ_m is the mean ordinate of dx/dy.

The mean ordinate can be readily computed by numerical and graphical integration to any desired degree of approximation. In the following examples we shall replace dx/dy by a five-point parabola as a convenient method of determining a weighted average, thus:

$$\mu_m = (1/90)(y\mu_o + 32\mu_1 + 12\mu_2 + 32\mu_3 + 7\mu_4) \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The canal is assumed rectangular and of great width, the walls and bottom in earth, $S_o = 0.0004$, $R = y = y_m$, discharge $Q = 20$ cfs, given the depth y_{10} = ten ft downstream, find the distance corresponding to y = six ft upstream. The cross-section of the canal gives Table 2, which allows us to draw Figure 1. Having drawn the Q curve $Q = 20 = yV$, we now read the distances from Q to the horizontal SY, and this gives Table 3.

Table 2--Determination of distance corresponding to y by cross-section of the canal

$y = R = y_m$	C	$b = 1/C^2R$	gy_m	S_o/gy_m
10	88.0	1.29×10^{-5}	322	12.4×10^{-7}
9	86.5	1.49×10^{-5}	290	13.8×10^{-7}
8	84.7	1.74×10^{-5}	258	17.5×10^{-7}
7	83.0	2.08×10^{-5}	225	17.7×10^{-7}
6	81.0	2.56×10^{-5}	193	20.7×10^{-7}

Table 3--Distances from Q to the horizontal SY

y =	10	9	8	7	6
	ft	ft	ft	ft	ft
$\eta = 1/\mu$, μ =	3.51	3.33	3.02	2.44	1.27

Applying the formula

$$\Delta x = (1/90)[(7/3.51) + (32/3.33) + (12/3.02) + (32/2.44) + (7/1.27)] \times 4 \times 10^4 \quad \ldots\ldots (6)$$

we find $\Delta x = 15{,}200$ ft. A greater number of steps would give a greater accuracy.

Figure 1 applies to a mild slope. We find in the α angle an M_1 curve along OU, and an M_2 curve above U.

We find an M_3 curve on a branch which is not figured but located in the β angle.

If the value of the slope increases enough, y_c will coincide with V_c, and η is indeterminate.

If the slope still increases, we obtain a steep slope. The curve S will be found in the angle α', and S_2 and S_3 in the angle β.

If $S_o = O$, S coincides with O, the channel is of zero slope, we obtain H_2 in α and H_3 in β'.

If S_o is negative and the slope is adverse, the point S falls below O and we obtain A_2 in α and A_3 in β'.

If the V lines are drawn on a stationary chart and the H lines on tracing paper so they can be moved up, moving the last ones up and down will easily give the intersections of the V and H lines corresponding to various slopes and various rates of flow.

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THE EFFECT OF FREEZING ON SOIL MOISTURE AND ON EVAPORATION FROM A BARE SOIL

Henry W. Anderson

Abstract--This paper reports the effect of soil freezing on the moisture distribution in the profile of a soil kept bare of vegetation. From successive soil-moisture samplings and by means of regression analysis of freezing and concomitant climatic data, the effect of soil freezing on surface soil moisture and on evaporation from the bare soil were obtained. Evaporation rates from the bare soil during freezing periods are compared with those from brush-covered soil during the same periods, with those from bare soil during similar nonfreezing periods, with those from a free water surface during the same periods, and with the calculated values for the same periods. Freezing of the bare soil caused the surface to become and remain wet, and greatly increased evaporation.

Introduction--Soil moisture and evaporation from bare soil are greatly affected by freezing of the soil. During soil freezing, water is drawn to the freezing layer from lower depths of the soil. When thawing occurs, the water in this layer may be subject to high evaporation rates. Frequent freezings and thawings of a bare soil may thus cause losses of soil water which are much greater than the combined transpiration-evaporation losses from an adjacent brush-covered soil where no freezing occurred.

At Northfork, California, where nightly freezing and daily thawing of the bare soil frequently occurred, it was observed that during rainless periods of from one to three weeks the surface half-inch or so of the soil would become and remain very wet--near the liquid limit of plasticity. A study of the soil-moisture data and the associated soil freezing was made to determine what effect freezing had on the soil moisture in the profile and on evaporation from the soil.

Review of the literature--Although no reports could be found concerning the effect of freezing on evaporation losses from the soil, some reports show the effect of freezing in bringing moisture to the surface of the soil. Restricting the review to those reports which show moisture movement from soil that was below the moisture equivalent or field capacity, the work of the Russian workers CHIRRIKOV and MALUGIN [see "References" at end of paper, 1926] deserves first mention. They reported the movement of water upward and the occurrence of a dry layer under the frozen soil. Inspection of some of their data shows that the driest zone occurred at the nine- to 18-inch depths below the surface, and that marked drying occurred to a depth of 30 in. The soil moisture at the ten-inch depth was reduced from what was apparently the field capacity, 18.5 per cent, to a moisture content of 11.1 per cent in a period of only 13 days. CHIRRIKOV and MALUGIN attribute this result to vapor movement upward.

Data of BESKOW [1935] show upward movement of water into a freezing layer which reduced the moisture content of the underlying soil to less than six per cent moisture, despite the fact that the capillary saturation (approximately the moisture equivalent) was greater than ten per cent. Beskow's total depth of soil was only about three in. Some data of LOCHHEAD [1924], who studied the effect of freezing and moisture content of the soil on microorganisms, show that when a sandy-loam soil was frozen to a depth of eight in, the moisture content at the ten-inch depth was reduced from an original moisture content of 12.4 per cent to a low of 6.4 per cent. From these three reports, the conclusion may be drawn that freezing does draw moisture from soil that is well below the field capacity in moisture content.

Experimental site--The soil-moisture and climatic data were collected at Northfork, California, elevation 2750 ft, latitude 37° N, on the western slopes of the Sierra Nevada, in the Upper Sonoran Life Zone. The climate is Mediterranean, and is characterized by comparatively mild temperatures, winter rains, and long periods in the winter without snow. The experimental site was situated above the mouth of a draw, midway up a 30 per cent slope on a west exposure. The soil was an immature gravelly, sandy-clay loam of the Holland series. The surface soil had a moderate amount of organic matter and was gray brown when dry and dark gray when wet. The moisture equivalent averaged 18 per cent in the zero- to three-inch layer and decreased to 14 per cent at the three-foot depth. Subsurface drainage was rapid on the slope. Soil-moisture samples were taken from under the brush and from a 14-foot square plot that was kept bare of vegetation and trenched annually to prevent entry of roots from the surrounding brush vegetation, which was 20 ft distant from the bare area. The temperature data were taken daily at 08^h00^m in a standard Weather Bureau shelter, located approximately 40 ft from the soil-moisture sampling areas. Precipitation data, which were determined daily from standard Weather Bureau rain gages, were the average of three gages situated within a 60-foot radius of the soil-sampling areas. The wind velocities were very light, averaging less than four mph at the top of the brush. Depth of freezing of the soil was determined at 08^h00^m daily. More details regarding the experiment area and its relation to the region as a whole, together with maps, are given in an article by ROWE [1941].

Factors affecting soil moisture--It is appropriate, first, to review the factors which affect soil moisture. The moisture content of any given layer of the soil at any time t depends upon the initial moisture content at some previous time t_o and upon the additions and losses of moisture during the interval between t_o and t. Soil moisture may be expressed symbolically, without regard to units, by using the following equation:

$$M_t = M_{t_o} + (P - I - Q_s) + (C - E - T) + (Y - S) \qquad (1)$$

where the factors are grouped into three main groups: (1) The "supply factors," P being the precipitation, I the interception losses, and Q_s the surface runoff; (2) the factors concerned with vapor exchange with the atmosphere, C being condensation or sublimation gain by the soil, E the evaporation losses, and T the transpiration losses; and (3) the water movement factors, Y being the gain from below and S being the seepage or vapor losses downward. Other groupings of the factors are, of course, possible, but these are convenient for the purposes of this study. In attempting to evaluate any one of the above factors, or any group of factors, it would be necessary to measure all others or eliminate the others by choosing periods when they were zero. For the bare soil being studied I and T were zero, and by considering only "net" evaporation the C and E terms were combined. The water-movement factors gave the most trouble. Seepage has always been considered the most difficult factor to measure. This paper will show that upward movement of water, Y, is also important during periods of freezing of the soil and that it greatly increased the evaporation, E.

Methods of study--Two methods of study of the effects of freezing on surface soil moisture and on evaporation were used. The first involved study of changes in soil moisture in the profile between successive soil-moisture samplings during periods when no precipitation had occurred, when seepage was zero, and when vapor movement was upward. The second method utilized multiple correlation and regression to relate the soil-moisture content to a simple combination of climatic factors and "time" as used by ZINGG [1943], with freezing as an added variable. In the second method, the seepage is eliminated by studying only the zero- to three-inch depth of soil, and since the soil samples were usually taken 48 hr or more after the end of the precipitation, drainage from this depth of soil was essentially complete.

Successive soil-moisture sampling method--By selecting early winter periods, before the soil profile had become wetted through, it was possible from successive soil-moisture samplings to study the changes in the moisture content for various depths. Since during these periods the deeper depths of the soil were warmer than the upper layers, movement of liquid moisture and vapor in the soil was upward, and no downward losses of moisture from the soil occurred. These were the only periods when evaporation losses could be determined with certainty by soil-moisture sampling.

The results for a bare soil showed a rapid and relatively large upward movement of water and large evaporation losses during freezing periods. Table 1 gives the results of soil-moisture samplings during one such ten-day period in January, 1939, when freezing occurred every night during the period, and complete thawing occurred every day. The daily depth of freezing varied from 0.1 to 0.7 in, averaging 0.44 in. For the ten-day period, net water losses from the soil profile by foot depths were: from the zero- to 12-inch layer, 0.24 in; from the 12- to 24-inch layer, 0.17 in; from the 24- to 36-inch layer, 0.53 in; and from the 36- to 48-inch layer, 0.08 in. Therefore, the net evaporation loss from the bare soil for the period was 1.02 in of water, over one-half of which had been drawn upward from the 24- to 36-inch depth. The moisture content of the 30- to 36-inch layer was reduced to less than nine per cent, despite the fact that the moisture equivalent of this soil was 16 per cent (the permanent wilting percentage was six per cent). Of the 9.13 in of water in the soil at the start of the period, 4.47 in were required to satisfy the wilting percentage, leaving 4.66 in available for plant growth. The ten-day evaporation of 1.02 in amounted to a loss of 22 per cent of the total amount of water available for plant growth.

In contrast to these results from a bare soil, no freezing occurred under the brush-covered area during the same period, and there the transpiration-evaporation loss of water from the soil profile amounted to only 0.25 in. Free water-surface evaporation from a standard Weather Bureau pan was only one-twelfth of the loss from the bare soil--only 0.08 in for the period.

Table 1--Changes in soil moisture of a bare soil during a ten-day period when daily freezing and thawing occurred, January, 1939

Soil depth	Moisture[a], January			Apparent density	Water content, January			Water loss, between January		
	9	13	19		9	13	19	9 - 13	13 - 19	9 - 19
in	pct	pct	pct	gm/cc	in	in	in	in	in	in
0 - 3	19.20	19.17	16.66	1.27	0.732	0.730	0.635	0.002	0.095	0.097
3 - 6	17.22	16.78	15.94	1.27	0.656	0.639	0.607	0.017	0.032	0.049
6 - 9	16.57	16.09	15.87	1.27	0.631	0.613	0.605	0.018	0.008	0.026
9 - 12	16.68	17.13	14.96	1.27	0.636	0.653	0.570	- 0.017	0.083	0.066
12 - 18	15.95	15.34	15.46	1.37	1.311	1.261	1.271	0.050	- 0.010	0.040
18 - 24	16.23	14.86	14.62	1.37	1.334	1.221	1.202	0.113	0.019	0.132
24 - 30	15.97	13.98	13.38	1.37	1.313	1.149	1.100	0.164	0.049	0.213
30 - 36	12.44	10.48	8.75	1.45	1.082	0.912	0.761	0.170	0.151	0.321
36 - 48	7.96	8.38	7.54	1.50	1.433	1.508	1.357	- 0.075	0.151	0.076
Totals					9.128	8.686	8.108	0.442	0.578	1.020

[a]Moisture as a per cent of the weight of soil dried in an oven at 105°C

Soil and air temperatures during the period were secured. The mean daily maximum and minimum air temperatures were 56°.5 F and 31°.4 F, respectively. Soil-temperature ranges were: At the half-inch depth, mean daily maximum 55°.7 F and mean daily minimum 27°.8 F; and at the 12-inch depth, mean daily maximum 35°.5 F and mean daily minimum 35°.3 F.

A similar case was observed during an 11-day period in December, 1937. During this time the evaporation loss from the bare soil, when freezing and thawing occurred daily, was 0.96 in; whereas the evaporation-transpiration loss from the brush-covered soil for the same period was only 0.28 in. The net water losses from the bare soil were; 0.34 in from the zero- to 12-inch layer, 0.44 in from the 12- to 24-inch layer, and 0.18 in from the 24- to 36-inch layer. In contrast to the first period reported, this time the major part of the water loss was from the soil above the 24-inch depth. This occurred because the deeper soil in this second instance was relatively dry at the start of the period. In both instances the final moisture contents of the soil layers below 24 in were nearly identical.

Checks of measured evaporation for both periods were made by dividing the total number of grams of water in a sample by the area of the sampling tube, thereby eliminating any differences due to the effects of soil density. Checks were also made by using the soil-moisture determinations that were taken before and after the period for which evaporation loss was calculated, and making allowance for precipitation, runoff, and interception by the vegetation. These checks all indicated that the losses were actual, and substantially in the amounts given.

Comparison of the evaporation rates from the bare soil when no freezing occurred during periods similar to the above showed that the evaporation rates were from 0.02 to 0.04 in/day for six- to ten-day periods; that is, they were only about one-fourth to one-half as great as when freezing occurred.

Regression analysis method--Although the two early winter periods reported above were chosen because they occurred before the complete soil profile had become wet, there is no reason to assume that freezing would not affect the surface soil moisture and evaporation from the soil during other freezing periods in the winter, after the soil profile has become wet. The second method of study permits evaluation of the effect of freezing on the surface soil moisture during the whole winter period, and offers a means of estimating evaporation losses affected by freezing.

The method includes: (1) Determination of the relationship of soil moisture to various climatic factors, including freezing; (2) expression of the change of soil moisture as a function of time following a rain, when freezing was zero. This change equals the evaporation rate, with certain limitations as to the length of the period to which it can be applied; (3) expression of the evaporation rate as a function of the soil-moisture content. From this the evaporation rate and total evaporation during an interval is expressed as a function of the climatic factors, including freezing. The last is based on the assumption that as freezing affects the soil-moisture content, the evaporation rate in turn is affected; (4) comparison of the evaporation as determined by the equations with the actual measured evaporation.

Soil moisture as a function of climatic factors--Nearly all of a long list of commonly measured climatic factors probably can be shown to affect soil moisture, as, for example, amount of precipitation, air temperature, dew point, vapor pressure, cloudiness, wind velocity, free water-surface evaporation, and solar radiation. But a simple combination of precipitation and air temperature, together with a "time" factor has been shown by ZINGG [1943] to be sufficient for a good estimate of soil moisture in a Shelby loam soil in Missouri. In the analysis of the Northfork data, advantage was taken of the findings of Zingg as to the use of variables and the logarithmic relationship between the variables. Some exploratory curves were drawn which indicated that the logarithmic relationship between the variables is satisfactory. In order to use a logarithmic relationship, zero freezing was, for all purposes, given a value of 0.1 in. Multiple correlation and regression analyses between 67 soil-moisture determinations and the concomitant climatic data were made. These data consisted of three years' records (1937-40) of soil moisture that had been taken in the intervals between the first fall rains, usually in October, and the last spring rains in May. Soil-moisture samples taken under snow were excluded from the analysis.

The variables used in the multiple correlation and regression were: M, estimated percentage of soil moisture of the zero to three inch soil layer; P, total rainfall in inches for 21 days prior to moisture determination; T, mean 21-day temperature in degrees F prior to moisture determination; N, time in days since occurrence of a rain storm sufficient to wet the top three inches of the soil to its field capacity; and F, sum of the daily depths of freezing in inches, for the period covered by N. With the exception of a slight change in N and the addition of F as a variable, the variables are those used by ZINGG [1943].

Determining the relationship between soil moisture, M, and the climatic variables, P, T, N, and F, gave a multiple correlation coefficient of 0.851, which is highly significant. The regression equation (using each variable expressed as its log to the base ten) was found to be

$$\log M = 2.9418 + 0.0345 \log P - 0.9589 \log T - 0.1660 \log N + 0.0719 \log F \quad \ldots\ldots (2)$$

with a standard deviation of ± 0.0703 log units or an equivalent of about ± 2.6 per cent moisture at 16 per cent soil moisture. The regression coefficients for log T, log N, and log F were all highly significant; however, that for log P was not significant. Dropping log P as a variable from the regression equation gave

$$\log M = 3.0376 - 0.9951 \log T - 0.1936 \log N + 0.0772 \log F, \text{ for } N > 1 \quad \ldots\ldots\ldots (3)$$

with a standard deviation of ± 0.0716 log units or an equivalent of about ± 2.7 per cent moisture at 16 per cent soil moisture. The correlation coefficient using these variables was 0.844, which is highly significant. The regression coefficients were all highly significant when tested by the "t" test; so this equation will be used in subsequent developments.

Evaporation rate when no freezing occurs--Since the variable N is the time in days since a rain occurred which was sufficient to bring the zero- to three-inch layer of soil to field capacity, it is also the number of days during which evaporation has been occurring from the soil. When sufficient time has passed after a rain storm for the zero- to three-inch layer of soil to drain to field capacity, $N>1$; then the change of soil moisture with time, N, is the evaporation rate in per cent of soil moisture per day. (Per cent soil moisture times a conversion factor of 0.0381 gives in depth of water.)

Figure 1, curve A, shows the change of soil moisture with time, N, when no freezing occurred in the interval. The evaporation rate may be expressed as a function of N when freezing is zero by using equation (3); expressing it as a power function and differentiating gives $M = 912.8\ T^{-0.9951} N^{-0.1936}$ and $dM/dN = -176.72\ T^{-0.9951} N^{-1.1936}$.

$$\log E_{\text{per cent}} = \log(-dM/dN) = 2.2472 - 0.9951 \log T - 1.1936 \log N, \text{ for } 1 < N < 11 \quad \ldots (4)$$

where $E_{\text{per cent}}$ is the evaporation rate in per cent soil moisture per day. Adding the log of 0.0381 converts the evaporation rate to in/day, E_{in}, for any particular day after the storm.

$$\log E_{in} = 0.8281 - 0.9951 \log T - 1.1936 \log N, \text{ for } 1 < N < 11 \quad \ldots\ldots\ldots\ldots (5)$$

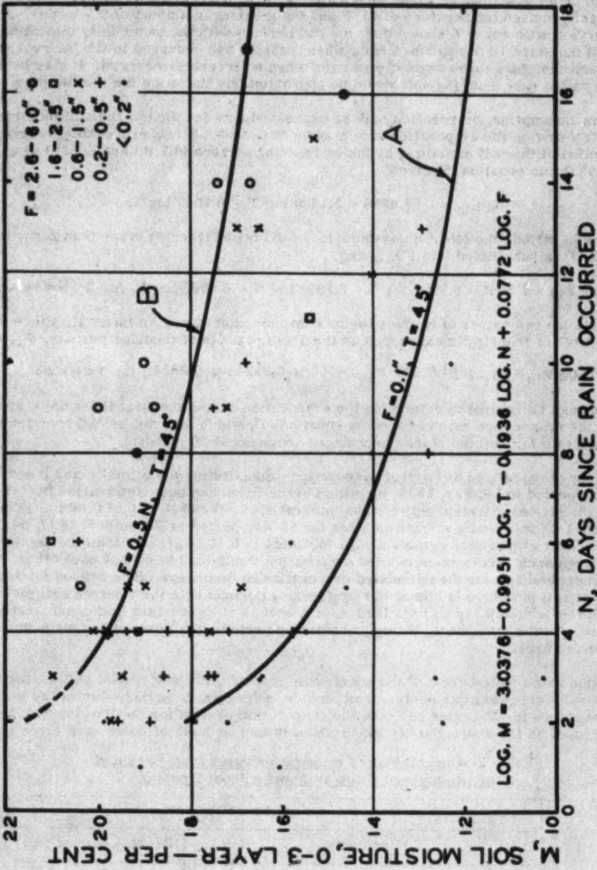

Fig. 1--Effect of freezing on the relationship between the soil-moisture content of the zero- to three-inch layer of the soil and the time in days since rain occurred

By integration, the total evaporation from the zero- to three-inch depth of soil during a period when freezing is zero is obtained.

$$\text{Total } E_{in} = 34.77\, T^{-0.9951}(N_1^{-0.1936} - N_2^{-0.1936}), \text{ for } 1 < N < 11 \qquad (6)$$

Evaporation rate when freezing occurs--During periods when freezing occurred, the soil moisture remained high for as long as three weeks after a rain. This is shown by curve B, Figure 1, for an arbitrarily chosen temperature of 45°F and for freezing in amount of 0.5 in/day. A comparison of curve B with curve A shows that, for two periods with the same daily mean temperatures, the soil moisture 16 days after a rain, when freezing had occurred in the interval, was the same as the soil moisture three days after a rain, when no freezing occurred. It may be assumed that the evaporation rate from the soil would be approximately the same for the two days also.

Using this assumption, evaporation may be expressed as a function of the soil moisture, and the effect of freezing on the evaporation rate may be evaluated. First, expressing the evaporation rate as a function of the soil moisture, by taking freezing as zero (0.1 in) and substituting log N from equation (3) into equation (5) gives

$$\log E_{in} = -17.4236 + 5.1400 \log T + 6.1653 \log M \qquad (7)$$

Then, in order to include the effect on evaporation of values of freezing other than zero, log M from equation (3) is substituted into (7), giving

$$\log E_{in} = 1.3041 - 0.9951 \log T - 1.1936 \log N + 0.4760 \log F, \text{ for } 3 < N < 14 \qquad (8)$$

Integrating between two values of N gives the total evaporation during an interval, where for convenience the depth of freezing is expressed as the average depth of freezing per day, F_{av}:

$$\text{Total } E_{in} = 71.32\, T^{-0.9951} F_{av}^{0.4760}(N_2^{0.2824} - N_1^{0.2824}), \text{ for } 3 < N < 14 \qquad (9)$$

Equation (9) cannot be applied to determine the evaporation during the first three days after a rain because the evaporation rate is based on equation (7), which may not be extrapolated to give the evaporation rate for soil moisture percentages above about 20 per cent.

Comparison of calculated and actual evaporation--Substituting the climatic and freezing data for the ten-day period in January, 1939, for which evaporation had been determined by soil sampling, into equation (8) gave evaporation between the interval of N = 3 and N = 12 of 0.88 in. This is 0.14 in less than the 1.02 in actually measured. For the 11-day period in December, 1937, on the other hand, the calculated evaporation came out 1.14 in, which is 0.18 in greater than the measured amount. Although such errors in calculated evaporation would tend to cancel each other, the general tendency would be for the calculated evaporation to be too low. The reason for this is that the surface soil moisture is higher during freezing periods than the average soil moisture of the zero- to three-inch soil layer, because freezing occurs at the surface and concentrates the moisture there. On the other hand, during nonfreezing periods, the reverse is true because the surface soil dries first.

Evaporation rates from bare soil during freezing periods, brush-covered soil during the same periods, bare soil during similar nonfreezing periods, a free water surface during the same periods, and calculated values for the same periods, the evaporation results for the ten-day and 11-day periods, expressed as the average daily evaporation in inches depth of water, are given in Table 2.

Table 2--Comparison of evaporation rates from bare and brush-covered soils, with and without freezing

Dates	Evaporation rate					
	Bare soil				Brush-covered soil	Free water surface
	With freezing		Without freezing		Without freezing	
	Actual	Calculated	Actual[a]	Calculated	Actual	
	in/day	in/day	in/day	in/day	in/day	in/day
Jan. 9 - 19, 1939	0.10	0.09	0.03	0.03	0.025	0.008
Dec. 20 - 31, 1937	0.09	0.10	0.03	0.03	0.025	0.008

[a] Not for the same periods, but for similar six- to ten-day periods.

Discussion--It should be emphasized that in equation (5) the evaporation is applicable to changes in the moisture content of the zero- to three-inch soil depth only. For values of N greater than ten days, the evaporation rate from the soil profile as a whole, during periods with zero freezing, was greater than is indicated by the change in curve A, Figure 1, because the lower soil depths also lost some water. However, this does not affect the prediction of evaporation during periods of freezing, for only the high moisture contents, associated with small values of N of curve A, were effective.

Equations (8) and (9), in some uses, depending somewhat on the distribution of freezing, will give too high an evaporation rate for the first few days after a rain and too low an evaporation rate for values of N greater than 14 days. However, the method here used could be improved if special soil samplings were taken so that the moisture content of the surface inch of soil could be related to the loss of moisture from the whole soil profile during periods of zero seepage.

Although the data from this study do not permit a rigorous explanation of the mechanism of water movement upward under the influence of surface soil freezing, the findings as to the rate of movement and the distribution of the moisture in the profile may be inspected in the light of the various theories as to the principal mechanism. Vapor movement due to the vapor pressure gradient associated with the surface coldness was considered by CHIRRIKOV and MALUGIN [1926] to be the cause of upward movement. Thermal gradient effects on water movement in soils as found by BOUYOUCOS [1915] might be another cause. Tensions in the water films adjacent to the freezing soil, as conceived by TABER [1930] might be the principal operating mechanism. Or a number of causes might be operating simultaneously at nearly the same or at widely different rates.

Vapor movement under temperature gradients and the associated vapor pressure gradients would account for only a very small fraction of the movement if the rates found by BOUYOUCOS [1915] are compared with the observed rates. Another reason for rejection of vapor movement as the principal mechanism is that according to data given by CHIRRIKOV and MALUGIN [1926] the variation of the rate of movement with changes in the moisture content was much greater than would be expected from the rather small changes in the vapor pressure gradient associated with the range of moisture contents studied.

Thermal gradient movement as found by BOUYOUCOS [1915] might have been and probably was effective, but a comparison of the data indicate that less than one-tenth of the movement could be accounted for in this way.

Movement under tensions set up in the water films adjacent to the ice crystals seems most probably to be the principal machanism. An indication of the magnitude of such tensions is obtained from the freezing point depression (3°C). According to an equation given by ANDERSON, FLETCHER, and EDLEFSEN [1942], if it is assumed that the ice freezes out at one atmosphere pressure, the adjacent water is under a tension of 36 atmospheres. Under such tension the water could be expected to flow through the connected water films which extend downward into the soil. Since the water in any layer in the wet zone would be replaced by water from below; then the lower soil would dry first and a moisture distribution such as is given in Table 1 would result.

Summary and conclusions--Freezing of surface soil kept bare of vegetation had an important effect on the moisture content and the distribution of the moisture in the soil profile as shown by successive soil-moisture samplings and by regression analysis of the data.

Surface freezing drew water upward from soil depths as great as 36 in and caused rapid water movement from soil having a moisture content far below its moisture equivalent or field capacity.

Freezing of the soil by drawing water upward to the freezing layer caused the surface soil to become and remain very wet during rainless periods of one to three weeks.

Freezing of a soil kept bare of vegetation greatly increased the evaporation loss from the soil. The evaporation during freezing periods was three times as great as during similar nonfreezing periods, nearly four times as great as combined transpiration-evaporation from brush-covered soil during the same periods, and about 12 times as great as evaporation from a free water surface during the same periods.

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SUBMARINE RELIEF OF THE ALEUTIAN TRENCH

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Introduction--In 1874, the U. S. S. Tuscarora, homeward bound from Japan, obtained a number of widely-spaced soundings, indicating a depression on the south side of the Aleutian Islands. One of these soundings indicated a depth of 4037 fathoms off Attu Island. From these limited data, geologists predicted a trench would be found paralleling the entire Aleutian Arc.

With development of echo sounding equipment in the 1920's, exploration of this region has continued at an accelerated rate. About 16 years ago, the United States Coast and Geodetic Survey evolved an economical plan for a series of sounding lines across the Gulf of Alaska and the Aleutian Trench. To date an excellent uniform coverage of these waters has been achieved and consists of about 60 lines crossing this region at intervals of about 15 nautical miles (see Fig. 1). The number of soundings obtained is about 45,000.

North face of Trench--Briefly, the relief of the Aleutian Trench (see Fig. 2) can best be divided into three principal parts as follows: First, the north face of the Trench, which is likewise the continental slope, and which is adjacent to the continental shelf bordering the mainland and the island arc to the north; second, the bottom or axis of the Trench; and third, the outer slope or south face of the Trench.

The inner north face of the eastern half of the Trench ranges from 20 to 70 miles in width, and descends at a rate of about three to four degrees, but may locally exceed 30 degrees near the bottom of the Trench (see Fig. 3). In such instances, the relief consists of an escarpment. Off Cape St. Elias, such an escarpment ranges in height from about 1600 ft to over one mile. It was in this region, in the year 1899, that an earthquake at Yakutat Bay resulted in a vertical land uplift of 47 ft.

A number of submarine valleys are intrenched in this slope. These are well developed by coastal surveys of the United States Coast and Geodetic Survey from near Unimak Island to the

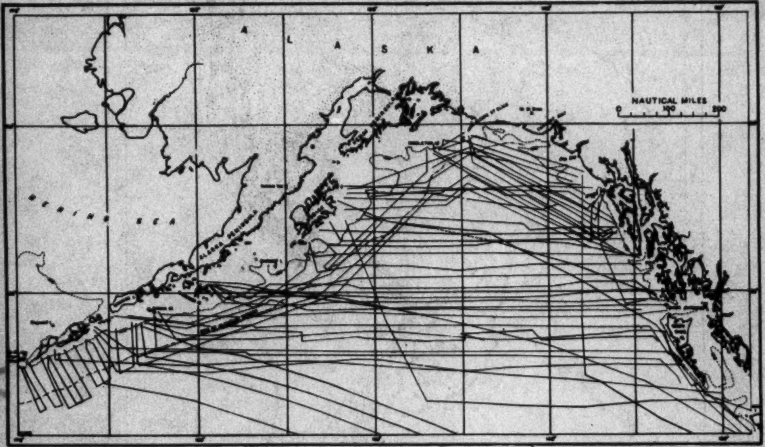

Fig. 1--Dead reckoning lines across the Gulf of Alaska

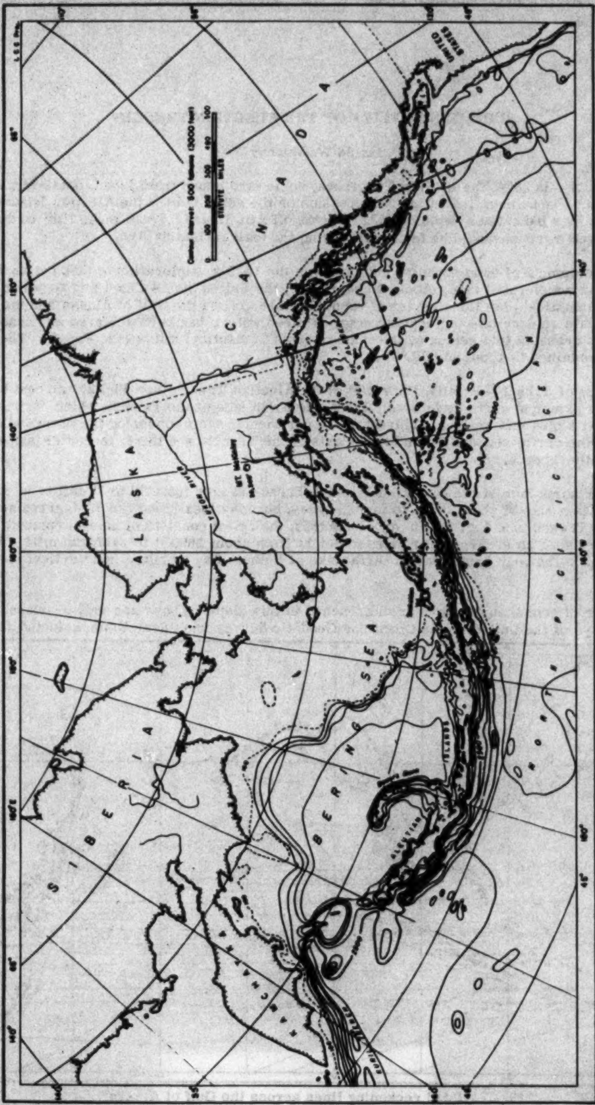
UNITED STATES
C A N A D A
A L A S K A
YUKON RIVER
MT. McKINLEY
S I B E R I A
K A M C H A T K A
B E R I N G S E A
ALEUTIAN ISLANDS
N O R T H P A C I F I C O C E A N
KURILE
Contour interval: 500 fathoms (3000 feet)
STATUTE MILES
0 100 200 300 400 500
120°
140°
160°W
160°E
140°
60°
45°

Fig. 2--The Aleutian Trench

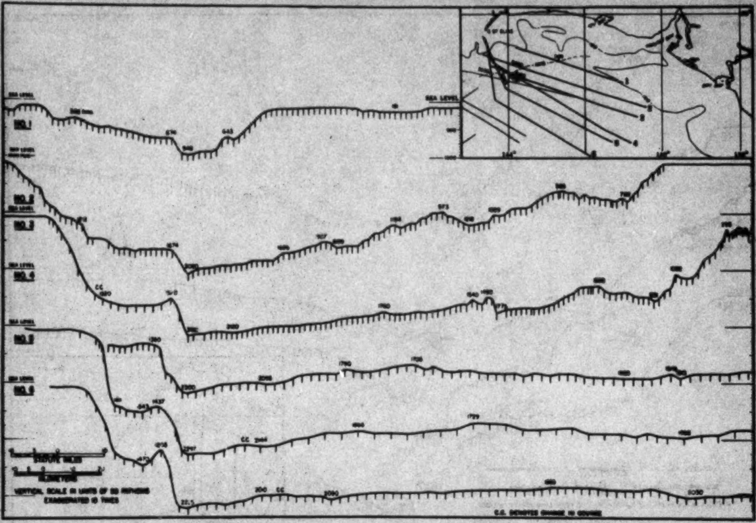

Fig. 3--Profiles of the eastern end of the Aleutian Trench

Islands of the Four Mountains. These valleys are known to descend to depths of at least 1500 to 2000 fathoms. With the acquisition of further data, we may discover that some valleys descend to even greater depths and have discharged their material onto the floor of the Trench.

Another feature, observed in the locality of Unimak Island to the Islands of the Four Mountains is a bench lying at depths of 2000 to 2500 fathoms. This bench is approximately 20 miles wide and at least 170 miles long. It is not known how far westward along the arc it extends. The earthquake of April 1, 1946, which is tentatively placed (May 17, 1946) at a position at latitude 53°.5 N, longitude 163° W, falls near the eastern end of this bench.

As a matter of interest, we may observe that the inside faces of island arcs, so prominent in the southwest Pacific region are characterized by coral reefs. Such a feature is absent on the Bering Sea side of the Aleutian Arc, probably because the colder waters of this latitude discourage such prolific colonies. However, living coral colonies, such as cup corals, do occur sporadically at various depths.

Bottom of Trench--The floor of the Trench lies about 20 to 70 miles off the edge of the continental shelf. Its length is about 2200 statute miles and extends from near Yakutat Bay westward to Attu Island on the extreme west. The bottom of the Trench lies in depths ranging from 2000 to 4200 fathoms. Depths approximating 4000 fathoms appear to exist in the 1000-mile stretch between Umnak and Attu Islands. From Umnak Island to near Cape St. Elias, a distance of another 1000 miles, the bottom consists of a gentle, undulating incline terminating near Cape St. Elias. The western half of this Trench, in contrast with the eastern half, is relatively unexplored.

Sounding-line profiles of the eastern half of the Trench (see Fig. 4) indicate that the bottom in the vicinity of Cape St. Elias is asymmetrically V-shaped, resembling a typical check-mark symbol. In proceeding westward, this shape changes to a concave saucer form and then blends into a graben-like structure.

The maximum difference in elevation, between the floor of the Trench and the nearby land features, occurs off Unimak Island near the middle of the arc of the Trench, the precise locality

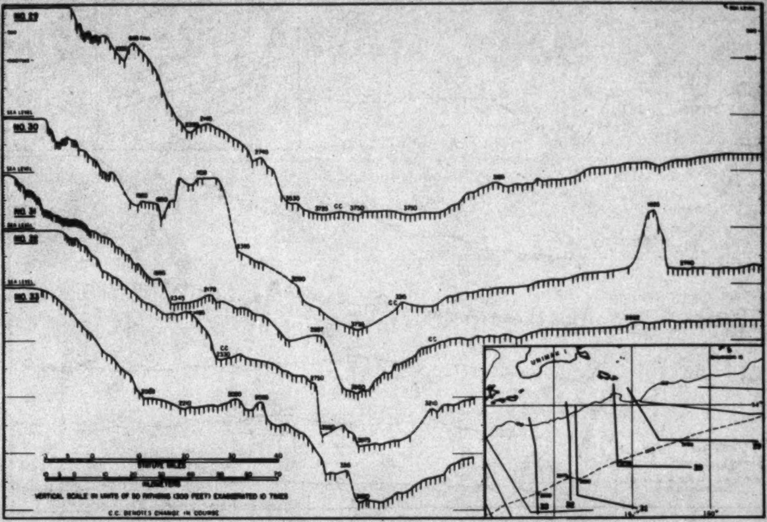

Fig. 4--Profiles of the Aleutian Trench in the vicinity of the Aleutian earthquakes of April 1, 1946

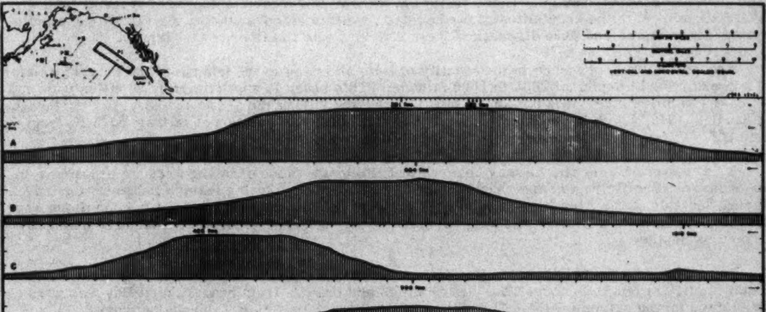

Fig. 5--Submarine mountains in the Gulf of Alaska

where the recent earthquake and tidal wave originated. Here, we observe that between the bottom of the Trench, about 3850 fathoms, and the summit of Shishaldin Volcano to the north, rising 9372 ft above sea level, there is a difference of approximately 32,500 ft, or six miles.

South face of Trench--The south face of the Trench, in contrast with the north face, has a more gentle slope, about one to four degrees, and is smoother in relief. Near Kodiak Island, two prominent bulges protrude into the Trench. The significant aspect of these bulges is that they are in alignment with a series of submarine mountains trending northwestward across the Gulf (see Fig. 5). Present data indicates that four such ranges trend across the Gulf. These mountains rise abruptly one to two miles above the bottom and reach to within 227 fathoms of the surface. In outline, the mountains are about ten to 25 miles wide and 15 to 70 miles long at the base. The tops may be either rounded or truncated. Some of the truncated portions also indicate a slight benching around the rims. The rounded periphery and steep sides of some of these mountains suggest that they may be of volcanic origin. When one pauses to visualize the foregoing dimensions, these undersea mountains are truly magnificent.

Conclusions--In concluding these comments, we are reminded that considerable research remains to be accomplished, consisting of more detailed sounding coverage as well as possible seismic investigations. We may further be assured that present development of this remote region is now progressing at an accelerated rate, and that the facts being revealed affect, not one, but several fields of research.

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U. S. Coast and Geodetic Survey,
Washington, D. C.

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DROWNED ANCIENT ISLANDS OF THE PACIFIC BASIN

H. H. Hess

Abstract

A large number of curious, flat-topped peaks have been discovered scattered over millions of square miles in the Pacific Basin. These peaks are roughly oval in plan and their slopes suggest volcanic cones. The remarkable feature about them is that they are truncated by a level surface which now stands approximately 750 fathoms (4500 feet) below sea level.

The writer discovered 20 of these peaks while at sea on the U. S. S. Cape Johnson, and 140 more were found in documents filed at the United States Hydrographic Office. These are all in the area between the Hawaiian Islands and Marianas. Some of the seamounts described by Murray [Bull. Geol. Soc. Amer., v. 52, pp. 333-362, 1941] in the Gulf of Alaska may be similar features.

After due consideration of the details of the flat upper surfaces of the peaks, it was concluded that the surfaces were probably developed by marine planation of ancient volcanoes, and that coral reefs were not developed on them as they were submerged. The hypothesis is advanced that the peaks might represent epochs of Pre-Cambrian volcanism and submergence in a sea which did not contain reef-building organisms.

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REPORT OF THE RESEARCH COMMITTEE ON RUNOFF, 1945-46

R. W. Davenport, Chairman

W. C. Ackermann
Bertram Barnes
Merrill Bernard
Bruce R. Colby
Howard L. Cook
E. S. Cullings
G. A. Hathaway
W. G. Hoyt
C. R. Hursh
Carl F. Izzard
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F. F. Snyder
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The variety of usage and even the confusion in the nomenclature and terminology of some fields of hydrology have been often remarked. The Committee on Runoff conceived the idea that it would be profitable to consider some of the terms which are especially pertinent to the field of runoff. That consideration was the principal Committee project of the past year and is featured in this report.

The Chairman sent a letter to the members of the Committee that was planned to draw out a symposium of opinions on the subject. A good starting point seemed to be the classification of water on the Earth. Meinzer's well-known classification was given: atmospheric water, surface water, and subsurface or subterranean water. Comments were solicited.

As being especially suited for consideration by this Committee, there was next presented the question, "What is runoff?" Definitions of runoff were given to illustrate some of the different schools of thought. Indications of the members' preference as to definition and pertinent comments were invited.

A brief statement was also made regarding the jurisdiction of the Committee on Runoff and the ramifications of runoff research in the fields of other research committees with view to eliciting discussion.

Twelve replies were received from the twenty members of the Committee addressed. Much careful thought was expended in the preparation of the replies, and the discussions are significant in showing a good cross-section of the views of hydrologists on some of the fundamental terminology of their science. Quotations of relevant parts of the Chairman's letter and the replies, arranged in the alphabetical order of the names of the writers, are attached as Appendix A. The replies are summarized below in relation to the three principal subjects.

Classification of water on the Earth--The following statement is quoted from the questionnaire: Probably one of the most basic classifications of water is the following, as given by MEINZER [see "References" at end of report, 1923], 'The water of the Earth can be divided into three parts: That which occurs in the atmosphere, that which rests on the surface of the solid part of the Earth, and that which occurs below the surface.' These three parts are commonly termed atmospheric water, surface water, and subsurface or subterranean water. If members of the Committee have any significant differences concerning this classification, it will be helpful if they will advise me.

The Meinzer definition was approved. Ramser suggested the substitution of "occurs on the surface" for "rests on the surface" as applying better to water moving in streams.

Ackerman and Barnes prefer "subterranean" to "subsurface." This preference is authoritatively supported [MEINZER, 1939].

Definition of runoff--The following definitions of runoff were given in the questionnaire as typical of those which are in use:

MEINZER [1923]: 'Runoff is the discharge of water through surface streams . . . The runoff of a drainage basin is the water that is discharged from the basin as surface water."

MEYER [1942]: "Runoff represents precipitation returning to the sea or to inland bodies of water. It is that portion of the precipitation that appears in surface streams . . ."

Considered in relation to the classification of water on the Earth, these definitions seem in harmony on the proposition that runoff is surface water. Surface water thus denoted as runoff may have passed through a groundwater phase somewhere on its travel, but at the point under consideration, it is surface water.

These definitions are not acceptable to all. For instance, the following draft of a definition of runoff has recently come to hand: "Runoff is drainage from the land of the excess in precipitation beyond that removed by evaporation and transpiration . . . Part of this drainage is direct runoff through surface and subsurface channels, and part is groundwater flow, all of which ultimately combine as stream flow."

Another definition is suggested by HURSH [1936]: "Runoff is the sum stream discharge from a drainage basin including both surface and subsurface runoff." (Here the last "runoff" is apparently used in the sense of "flow.")

CONDRA has stated [1944]: ". . . the comprehensive meaning of the term runoff to include both surface and groundwater movement, although desirable, is not employed very generally."

This, at least, indicates Condra's preference for a definition to include both moving surface water and moving ground water.

The preferences of the Committee members, as might be anticipated, are quite varied and reflect the individual usage as well as abstract ideas of a proper definition. The following shows results of an effort to rate the number of preferences for the runoff definitions considered: Meinzer, four; Meinzer with revision, one; Meyer, one; Meyer with revision, one; combination Meinzer and Meyer, two; and other, three.

The Meinzer and Meyer definitions have the common characteristic that "runoff" is "surface water." The "other" definitions have the common characteristic that "runoff" includes both "surface water" and "subterranean water." The vote of preference of nine to three for Meinzer or Meyer, or some modification of them, seems fairly indicative of a predominating usage in that respect.

If runoff is to include surface water only, what term can be used to represent the total water of the drainage system, both surface and subterranean? Wilm and others suggest "water yield" for that purpose, but that has not run the gantlet of consideration by members of the Committee.

The Meinzer definition permits the double use of runoff, both as a volume and a rate of flow, and there is wide usage in those ways. Snyder prefers the Meyer formula because it precludes the use of "runoff" as a rate of flow. Colby makes the following discriminating observation: "Any definition that makes runoff synonymous with discharge of surface water or with the combined discharge of surface water and ground water tends to waste the term 'runoff.' On the other hand, some word is needed to designate that portion of precipitation which immediately or eventually becomes flow in surface streams."

"Runoff" is used primarily, it is believed, in a contrasting association with rainfall or precipitation, and more generally in a quantitative than in a rate sense. The use of any word in two or more senses tends to result in uncertainty and confusion. Assuming that other satisfactorily distinctive terms are available to meet the needs, use of "runoff" only in a quantitative sense would tend to promote clarity in hydrologic expression. Doubtless such restricted usage would not be popular with some who are accustomed to other usage and who do not feel the need for such discrimination.

Jurisdiction of Committee on Runoff--The pertinent part of the Chairman's letter follows:

By general acceptance the jurisdiction of the Committee on Runoff has included the phenomena of surface water movement. This field has, however, touched or overlapped at some points those of the Committees on Dynamics of Streams and Infiltration.

However, the jurisdiction over the phenomena of groundwater movement has been predominantly in the Committees of Infiltration, Physics of Soil Moisture, and Ground Water.

The study of characteristics of runoff considered as water in a surface stream leads inevitably to correlation with the causative precipitation and the many influencing physical features of the drainage basin. It leads to the interpretation of soil and groundwater conditions in ways that seem to enter rather deeply into fields of research outside those for which in general the Committee on Runoff was especially selected and organized. This condition bespeaks the importance of the development of some of our concepts of runoff with the advice of and in close understanding with, other research committees that may be involved.

The replies of members show general appreciation of the peculiar overlap of interests of the Committee on Runoff with those of some of the other research committees. The need for understanding and coordination with other hydrology committees was emphasized.

It is planned to continue a similar discussion of phases of hydrologic terminology pertinent to runoff research during the coming year.

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U. S. Geological Survey,
Washington, D. C.

(Manuscript received July 26, 1946; presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 28, 1946; open for formal discussion until May 1, 1947.)

APPENDIX A--LETTER BY CHAIRMAN TO MEMBERS OF COMMITTEE ON RUNOFF AND EXTRACTS FROM REPLIES OF MEMBERS

Chairman's letter

November 26, 1945

Members of the Committee on Runoff,
Section of Hydrology,
American Geophysical Union

Gentlemen:

Letter of June 13, 1944, reporting to the Committee on a committee conference following the 1944 Annual Meeting, contains the following item: "The confusion in nomenclature and terminology (of runoff) was noted. It was the concensus that each writer of a paper should make quite clear his own usage of terms therein. Also it was thought that if more flagrant instances of the confusion were considered, some improvement might be made with respect to them. The time does not seem favorable for comprehensive consideration of nomenclature."

Even though the time may not be ripe for comprehensive consideration, there would seem to be possible benefit in a discussion among members of the Committee designed to exchange and clarify ideas on some fundamentals of runoff terminology.

Classification of water on the Earth--Probably one of the most basic classifications of water is the following, as given by MEINZER [see "References" at end of appendix, 1923]:

"The water of the Earth can be divided into three parts: That which occurs in the atmosphere, that which rests on the surface of the solid part of the Earth, and that which occurs below the surface."

These three parts are commonly termed atmospheric water, surface water, and subsurface or subterranean water.

If members of the Committee have any significant differences concerning this classification, it will be helpful if they will advise me.

Definition of runoff--There is known difference of ideas on the answer to the question, "What is runoff?" The definition of "runoff" is, of course, about the most fundamental in runoff terminology, and it seems particularly appropriate to canvass the ideas of the Committee on Runoff on the question.

Following are two well-known definitions of runoff:

MEINZER [1923]: "Runoff is the discharge of water through surface streams . . . The runoff of a drainage basin is the water that is discharged from the basin as surface water."

MEYER [1942]: "Runoff represents precipitation returning to the sea or to inland bodies of water. It is that portion of the precipitation that appears in surface streams . . ."

Considered in relation to the classification of water on the Earth, these definitions seem in harmony on the proposition that runoff is surface water. Surface water thus denoted as runoff may have passed through a groundwater phase somewhere on its travel, but at the point under consideration it is surface water.

These definitions are not acceptable to all. For instance, the following draft of a definition of runoff has recently come to hand:

"Runoff is drainage from the land of the excess in precipitation beyond that removed by evaporation and transpiration . . . Part of this drainage is direct runoff through surface and subsurface channels, and part is groundwater flow, all of which ultimately combine as stream flow."

Another definition is suggested by HURSH [1936]: "Runoff is the sum stream discharge from a drainage basin including both surface and subsurface runoff." (Here the last "runoff" is apparently used in the sense of "flow.")

CONDRA has stated [1944]: ". . . the comprehensive meaning of the term runoff to include both surface and groundwater movement, although desirable, is not employed very generally."

This at least indicates Condra's preference for a definition to include both moving surface water and moving ground water.

It will be much appreciated if the members of the Committee on Runoff will write me the definitions of "runoff" which they prefer: Meinzer's, Meyer's, or some other. Any pertinent comments and observations will be welcome. The results may not decide any issue, but they should be interesting and significant.

Jurisdiction of Committee on Runoff--By general acceptance the jurisdiction of the Committee on Runoff has included the phenomena of surface water movement. This field has, however, touched or overlapped at some points those of the Committees on Dynamics of Streams and Infiltration.

However, the jurisdiction over the phenomena of groundwater movement has been predominantly in the Committees of Infiltration, Physics of Soil Moisture, and Ground Water.

The study of characteristics of runoff considered as water in a surface stream leads inevitably to correlation with the causative precipitation and the many influencing physical features of the drainage basin. It leads to the interpretation of soil and groundwater conditions in ways that seem to enter rather deeply into fields of research outside those for which, in general, the Committee on Runoff was especially selected and organized. This condition bespeaks the importance of the development of some of our concepts of runoff with the advice of and in close understanding with other research committees that may be involved.

Comments by members of the Committee will be gratefully received.

It is hoped that the replies of the members of the Committee may be digested in a form suitable for inclusion in the annual report of the Committee. If successful, this canvass may be followed by another designed to clarify ideas of runoff terminology, for example, such as classification of runoff. Doubtless, other objectives are in order. Suggestions are solicited. It is hoped that all replies may be received by January 15.

Very truly yours,

R. W. Davenport, Chairman
Committee on Runoff

Extracts from replies of members

William C. Ackermann (Tennessee Valley Authority, Knoxville, Tenn.)--The status of terminology in hydrology is certainly confused, and I am inclined to agree with the Chairman that it cannot be completely adjusted at present. The reason for this, it seems to me, goes deeper than agreement upon terms for similar phenomena. For example, subsurface flow has always been termed underflow, interflow, etc. A single term for this type of flow could probably be selected and agreed upon if an authoritative group such as could be formed in the American Geophysical Union were to adopt a term. However, there is a more basic and difficult problem: There are prominent hydrologists of my acquaintance who do not recognize the existence of this type of flow. The only apparent answer is more knowledge, particularly in the field of observational hydrology.

Referring to the classification of water by Meinzer which the Chairman quoted, there seems to be no question as to its correctness from the standpoint of defining the location of water forms. In this definition there is no attempt to include the history of the water located in a particular class. But the confusion starts when the three classes are termed atmospheric, surface water, and subsurface or subterranean water, because the term "subsurface" is also used to define one particular type of runoff. This is only a problem of words.

The definition of runoff which is quoted, "Runoff is drainage from the land--" appeals to me more than the others because of its relative completeness. However, I would suggest adding deep-seepage loss to that removed by evaporation and transpiration.

My experience in the use of the term "runoff" has apparently been different from that of Condra, whom the Chairman quotes. In our organization, we use runoff and stream flow almost interchangeably. At least they both refer to flow in surface streams. When the stream flow or runoff is analyzed, the constituent parts are referred to as surface runoff and groundwater runoff, or surface runoff, groundwater runoff, and subsurface runoff.

Bertram S. Barnes (U. S. Weather Bureau, Los Angeles 12, California)--Classification of water--I believe that Meinzer's classification should be accepted, with the term "subterranean water" to be used in preference to "subsurface water." The possible confusion of the latter term with "subsurface flow" makes the former preferable.

Definition of runoff--Most hydrologists think of runoff from a basin as consisting of the water from natural sources within the basin that leaves the basin by visible channels. In tabulating annual runoff we do not usually include water brought into the basin by artificial means and discharged directly into a stream channel. The part of the flow that has entered the stream from underground sources, including return flow from irrigation, water spreading, or leakage of canals, is ordinarily included in the basin runoff even though some of the water may have been precipitated outside the basin. Certain western streams are sustained for long periods by water entering the basin underground.

Meinzer's definition is clear and concise but fails to exclude artificial diversions into the stream channel from sources outside the basin.

Meyer's definition brings in the concept of runoff as the part of the precipitation that will later appear in surface channels. It is obviously not intended to be applied to the specific runoff from a basin, because if reduced from general to specific terms it would exclude all water precipitated outside of the basin. The third definition quoted in the Chairman's letter is subject to the same objection. It also conveys the idea that all moving ground water ultimately appears in surface stream channels, which is not strictly true.

Hursh's definition is in agreement with Meinzer's if we give "stream discharge" its usual meaning: water flowing in surface channels.

I suggest that the definitions given by Meinzer and Meyer be combined in a more comprehensive statement, as follows: "Runoff is the discharge of water through surface streams. The runoff of a drainage basin is the portion of the water precipitated within the basin or emerging from the ground within the basin, that is discharged from the basin as surface water."

Jurisdiction of Committee on Runoff--It is fairly easy to discuss a topic such as precipitation, ground water, soil moisture, infiltration, or dynamics of streams without involving other hydrologic phenomena to any material degree. Discussions of runoff, however, will necessarily overlap several fields, because runoff as a topic cannot properly be separated from the several phenomena that cause and control it. It seems to me that the immediate purpose of the discussion, as distinguished from the extent to which the individual phenomena are discussed, should be to determine which committee has jurisdiction over it. The jurisdiction of the Committee on Runoff should properly cover work in which the immediate objectives are more closely related to runoff than to the phenomena assigned to the other research committees. I heartily approve of the proposal to canvass the members in regard to runoff terminology. A standard classification of runoff, even if only tentative, is badly needed at the present time.

Bruce R. Colby (U. S. Geological Survey, Lincoln, Nebr.)--Generally when different meanings of a word are well known and one of them is to be selected for exclusive use in the future, the one that is selected should be a meaning for which there is no convenient substitute. Any definition that makes runoff synonymous with discharge of surface water or with the combined discharge of surface water and ground water tends to waste the term "runoff."

On the other hand, some word is needed to designate that portion of precipitation which immediately or eventually becomes flow in surface streams. Thus the runoff of a drainage basin might be defined as that portion of the precipitation that appears in surface streams in the basin. This definition is like the second part of the definition given by Meyer.

If the first part of the definition by Meyer is to be completely consistent with the second part of his definition, the first part probably should be revised slightly to read somewhat as follows: "Runoff represents precipitation that returns toward the sea or toward inland bodies of water by flowing in surface streams, although previously it may have flowed underground." This slight revision of the first part of the definition given by Meyer is the definition which I prefer.

An objection to combining surface and subsurface flow from a basin into a comprehensive definition of runoff might be that many problems in hydrology do not particularly involve subsurface flow. Also the amount of this flow is frequently unknown or at least difficult to compute. In other words, runoff defined to exclude subsurface flow probably would be a more useful term than runoff defined to include it.

Edwin S. Cullings (Hydraulic Engineer, Watertown, N. Y.)--It seems to me that the terminology and definitions formulated by Meinzer in Water Supply Paper no. 494 should be followed. Meinzer's definitions are clear and comprehensive, and they have been in use for nearly 25 years. I can see no reason for material change.

I am opposed to the coinage of new words for old phenomena. One instance is the use of the word "quality" to express the heat of fusion of snow. This use seems to be quite prevalent around the United States Weather Bureau. The term "heat of fusion" is definite and clear, and it is understood by everyone who has studied high-school physics. Snow has a dozen qualities and, to my mind, it is highly improper to attempt to confine the meaning of the word "quality" to one of them. Doubtless other instances of this kind have come to your attention.

I hope the Committee will see its way clear to retain Meinzer's definitions and terminology.

Charles R. Hursh (Appalachian Forest Experiment Station, U. S. Department of Agriculture) Asheville, N. C.)--Classification of water on the Earth--For very general purposes, Meinzer's classification of water on the Earth is simple and easily understood, and I have no important differences to bring out other than that it offers very little explanation of the physical state of water either in the air or on or in the Earth.

Definition of runoff--An entirely acceptable definition of runoff is going to be difficult to draw up without first having some physical unit or area in mind. My comments refer to a drainage area with a definite drainage channel.

In considering the subject of water discharge from a drainage area, it is doubtful whether any one definition of runoff will be universally applicable in all physiographic regions unless it has a rather broad latitude of meaning. For example, in a granitic mountain formation one may locate a solid rock channel which may conceivably control a flow section for all the water discharged from the drainage area as runoff. At the other extreme, one recognizes sand-filled stream channels, which carry very little visible surface flow but which do carry considerable flow through the sand itself. A similar condition frequently exists in some mountainous regions, where drainage channels are naturally filled with angular rock debris, gravel, and sand. It is with this in mind that I have attempted to combine into the concept of runoff both the surface flow and any subsurface flow that may be taking place at a given point in a drainage channel [1936]. In these definitions, subsurface "runoff" is specifically associated with a given point of reference on the drainage channel. It was not to be confused with any form of subsurface stormflow or groundwater movements elsewhere on the watershed.

Although some qualifications may be required, I still prefer some concept of runoff that will include the total measurable discharge through an established drainage channel. This discharge may be entirely surface runoff, or it may include some subsurface flow through the loose sand and debris within a recognizable stream channel.

Of course, one can carry this line of thought still further. For example, in a mountainous, humid region one may find relatively narrow valleys, sometimes with meandering streams. Hence there is some movement along the high water tables across the entire valley floor. All of this movement is a form of ground water leaving a definite drainage area, although it is not generally recognized as runoff. It may be necessary, therefore, to consider that runoff is the readily measurable flow associated with a definitely recognizable drainage channel. In the above instance, the total discharge is made up of the easily measurable flow associated with the stream channel at the surface or through the channel fill, plus the discharge leaving the drainage area as ground water along the water table of the valley floor, plus deep seepage and the lateral groundwater movements away from the natural drainage lines.

Jurisdiction of Committee on Runoff--Undoubtedly the jurisdiction of the Committee on Runoff can best be arrived at through a mutual understanding of all the different hydrology committees as to what will be the emphasis of effort of each of several groups. Hydrology is not a science that can be separated into a group of entirely independent subjects, and progress in extending our knowledge of hydrology will come through a coordinated effort on a very broad front.

Karl Jetter (Division Office, Army Engineers, Omaha, Nebr.)--I am submitting ideas which have occurred to me in response to the Chairman's letter of November 26, 1945, inviting comments upon runoff terminology from the members of the Committee on Runoff. I found the subject interesting as I pursued its various possibilities, and, regardless of having obtained a solution, found the ideas served somewhat to clarify my thinking on the subject.

I am in accord with Meinzer's classification of water on the Earth. This classification is based upon occurrence of water above, upon, or beneath the Earth's surface, and the lines of classification are clearly defined.

The difference of ideas on the question of "What is runoff?" may be attributed in part to the attempt at multiple use of the word to cover several definitions based upon a combination of occurrence, state, and tense (in time), depending upon the reader to choose the exact meaning intended from the context. Ordinary usage generally associates runoff with surface waters. So for the defining of surface waters I turned to the United States Geological Survey Water Supply Papers--"Surface Water, Supply of--River--." Therein I found the opening sentence under "Scope of Work" as follows: "This volume is one of a series of reports presenting results of measurements of stage and flow made on streams, lakes, and reservoirs in the United States--. Measurements of the flow of streams and of the stage and contents of lakes and reservoirs have been made at . . . gaging stations . . . " This is in complete accord with Meinzer's classification of surface waters. A little further on under "Definition of terms" I found the word "runoff" in the definition for "second feet per square mile" and "runoff in inches." In the former I find it applied to "cubic feet of water flowing per second from each square mile of area drained, on the assumption that the runoff is . . . " In the latter--runoff . . . "is the depth to which an area must be covered if all the water draining from it . . . " These two definitions, both correct and accepted by usage, are examples of the multiple use of the word "runoff" which mitigates against a clear-cut definition of the word. These definitions have the water as flowing or as standing or having flowed and also bring in the concept of water yield by drainage from an area, where this yield would include that contributed by ground as well as surface waters. It would seem that both these definitions could substitute for the word "runoff" the equivalent of "drainage area yield" or just "drainage." This latter would be in accord with the dictionary primary definition of drain or drainage, and should preempt, although not destroy, the common usage of the word drainage as meaning the man-made works for draining water from small areas.

Returning now to a definition of "runoff," I would combine Meinzer's and Meyer's definitions and add a bit to them, thus, "Runoff represents precipitation draining from the land by flow over the Earth's surface, both in the well-defined channels of brooks and rivers and in the initial overland flow prior to collecting in the defined channels." I include rainfall to insure application of the word runoff to the hydrologic cycle. I believe the word runoff should retain the idea of flow in the active sense embodied in the word "run" indicating the short period of time between rainfall and the surface-water flow to the point of measurement. Also the concept of "free" running in open channels such as brooks and rivers, which would not be applicable to groundwaterflow, ordinarily slow moving in completely confined channels, should be included. The term runoff then could not be applied to the static bodies of waters as lakes and reservoirs, the contents of which I would term "drainage" or some adaptation of this word. Runoff, by its meaning of rapid flow, would also include most of the melted snow or rainfall which, although not entirely and wholly running off over the ground surface, would get into the stream channels within a short time after the purely surface flows.

The subject of infiltration, of course, must be integrated in any consideration of runoff. After it is deducted or accounted for, I consider infiltration would no longer be in the picture of runoff or the phenomena of surface-water movement. I believe infiltration might be considered in relation to ground water somewhat analogous to overland flow in runoff or pondage. Both are the initial stages of draining off the rain. "Ground water" is all inclusive, encompassing all water (in whatever form or condition) existing below the Earth's surface, and the tendency is to use it as applying to water in motion or static in storage. Infiltration to my mind is a type of ground water in motion, or groundwater flow. The basic definition of infiltration includes the idea of flow, or movement into. This is apparent as it does not require the modifying or added word "flow." Infiltration I consider ended when the percolating water joins a stored body of ground water such as the groundwater table, or some subterranean flow.

Hence the overlapping in connection with runoff and groundwater studies would start with the rainfall on the surface of the Earth, and perhaps infiltration need not be pursued much further in relation to runoff than overland flow is in relation to ground water. At least that is as far as I would go in relation to what I have proposed as a definition for "runoff."

Phillip Light (U. S. Weather Bureau, Seattle 4, Wash.)--There is a great need for exact and authoritative definitions of hydrologic terms, and I hope this matter of runoff definition can be carried to a successful conclusion. I have very little to offer on this subject except to add my vote for Meinzer's definition. My reasons are the simplicity of that definition, and the fact that by its use the quantity of "runoff" can be determined through direct observation. I would suggest that the terms "water yield" and "discharge," often used synonymously with "runoff," be subjected to a similar inquiry.

F. T. Mavis (Carnegie Institute of Technology, Pittsburgh, Pa.)--Among the definitions of runoff included in the Chairman's letter of November 26, 1945, I prefer the one given by Meinzer, with a small addition that is suggested by a consideration of drainage problems: "Runoff is the discharge of water through surface streams and artificial drainage conduits." I wonder if the inconsistencies implicit in the other definitions might be resolved by some such addition as I have made.

Webster's Unabridged Dictionary gives this definition of runoff: "The water which is removed from soil by either surface or under drainage; flowoff." Oddly enough, the term does not seem to be defined in Funk and Wagnalls with this connotation.

Apparently the use of "runoff" as a noun originated in western United States. In a paper by HERBERT M. WILSON [1891] this statement is made: "The State Engineers of California and Colorado have gauged several of the more important streams in their States, and from these and the rainfall on their basins we are enabled to obtain rough data from which the runoff of their minor branches may be ascertained with some degree of accuracy." Earlier papers in the Transactions of the American Society of Civil Engineers refer to "water that flows off after a rainstorm" and "water that runs off from hard surfaces."

CYRUS C. BABB [1892] refers to a column of figures which gives "the depth of runoff, or the depth in inches which a plain of the size of the drainage basin at this point would be covered, if the total flow for the month were spread over it."

A. FTELEY [1892] states: "The thing we are all after is knowledge of the flow of a given stream in cubic feet per second; of what our western friends call 'the runoff' and I imagine that if the measurement of cubic feet per second had been as simple a matter as measuring rainfall, we should now have a much greater knowledge on the subject than we actually have."

We can measure the flow of water in surface streams and in artificial drains. We need a clear-cut term for that discharge which we can both define and measure. Apparently the term "runoff" has been used as a noun for at least 55 years to denote that well-defined discharge that is readily measurable in surface streams and artificial drains. The wording suggested by Meinzer (with or without the addition suggested) meets the requirements of a definition, while some of the other wordings lack one or more of the essentials of a definition.

C. C. McDonald (U. S. Geological Survey, Tacoma 2, Washington)--The term "runoff" has been used very loosely in engineering literature, and I believe a thorough discussion of its use will be valuable. Perhaps some latitude should be allowed in the use of the term, and its definition might retain some flexibility through combination with an adjective. However, I am in favor of a more limiting definition than apparently exists at present.

I believe the second part of Meinzer's definition, "The runoff of a drainage basin is the water that is discharged from the basin as surface water" is the most commonly accepted usage. "Runoff" should certainly not be synonymous with "discharge," or "flow." I would prefer another term, such as "water yield" as suggested by Wilm and Jetter, to designate the total drainage, including subsurface flow from a basin. "Water yield" might be considered to include movements of ground water between basins, through the bed of the stream, or directly into the ocean in the case of coastal streams.

I submit the following suggested definition: "Runoff is the portion of the natural drainage from an area that appears as surface flow at the mouth of the basin."

The field of the Committee on Runoff undoubtedly includes the subject of infiltration, and possibly snow melt, evaporation, transpiration, etc. However, infiltration is only one of several phenomena of interest to the Committee on Runoff, whereas it is the primary concern of the Committee on Infiltration. Duplication of interest to this extent would seem desirable.

Meinzer's classification of the types of water of the Earth appears logical, and apparently is fairly well accepted. Subsurface or subterranean water is generally segregated into two classes: ground water and soil moisture. Soil moisture apparently includes all water above the water table. There appears to be some difference of opinion in respect to this classification of subsurface water. Perhaps a discussion of those terms would be enlightening.

C. E. Ramser (Department of Agriculture, Washington, D. C.)--It seems to me that the word "occurs" should be used in place of "rests" in Meinzer's classification of the water of the Earth, since it does not seem correct to refer to water moving in streams as resting.

With regard to concepts of runoff, I offer the following definitions that are under consideration by the Committee on Hydrology of the American Society of Agricultural Engineers:

Total runoff--The accumulated volumetric runoff from a drainage area for a definite period of time such as a day, month, or year, or it may be for the duration of a particular storm.

Surface runoff--Water which either reaches stream channels essentially as overland flow, or falls directly into the stream channels.

Subsurface storm runoff--Water which enters the soil but returns to the surface or appears in channels at a lower level without entering the groundwater table in the permanent zone of saturation.

Direct runoff--The total amount of surface runoff and subsurface storm runoff without entering the groundwater table in the zone of saturation.

I believe these definitions are essentially the same as appeared in a report on "Methods for Evaluating Rainfall-Runoff Indices and Relations," November 1939, prepared by a committee composed of Hoyt, Leach, Riesbol, Cotton, Hertzler, Panusio, and Langbein.

Hursh's definition of runoff conforms most nearly to the definitions of the foregoing terms.

Concerning jurisdiction of the Committee on Runoff, I would be in favor of combining the Committees on Runoff and Infiltration, since it is difficult to treat either of these subjects fully without involving the other.

Franklin F. Snyder (U. S. War Department, Washington, D. C.)--Meyer's definition of "runoff," although quite similar to that of Meinzer, is preferred by the writer because it clearly precludes the possible use of the term for rate of flow. The words "runoff" and "discharge" frequently are used loosely, and it is believed that "runoff" should not be used for the rate of flow. Meyer's definition also provides for use of the word in connection with observable phases of the phenomenon such as water running off the surface of the Earth or out of the ground into a channel.

The overlapping of jurisdiction of the various research committees is unavoidable, as the Chairman points out in his letter. The writer believes, however, that there can be no objection to the use of research data from one field to solve problems in a related field or later phase of the hydrologic cycle. The need for cooperation is quite evident.

H. G. Wilm (Sr. Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)--This is in reply to the circular letter of November 26, 1945, requesting suggestions on runoff terminology. As the Chairman points out, it does seem desirable to clear up a few of the more disputed or confused technical terms, even though we may not be ready to crystallize all of the nomenclature associated with runoff.

Meinzer's fundamental division of water into three classes seems to be sound, and I have no comment. As to the definition of runoff, however, I should think we ought to use that proposed by Meinzer and Meyer, since it seems to be logical and widely accepted. A similar definition was stated by the American Society of Civil Engineers in its 1937 glossary for hydraulics: "The portion of precipitation that appears as surface flow in streams." In addition, perhaps we do need a broader term which will include subsurface and groundwater discharges as well as surface stream flow; for this purpose I should suggest the term "water yield."

While I am at it, may I make one or two more suggestions on terms which seem rather unclear at present? When our terminology is crystallized we should distinguish between "runoff" as defined above, and "surface runoff" as the latter term is commonly used, meaning either the flow of excess precipitation over the land surface or that portion of stream flow which comes directly from the land surface. For flow over the land surface, the term "overland flow" is commonly used and seems to be most appropriate. Then "runoff" would be the flow of a surface stream at any point. Depending on the source of this runoff, it might be composed of "surface runoff" (derived from overland flow), "subsurface runoff" (from wet-weather springs), and "groundwater runoff" (from deeper springs and the groundwater table). Also, "water yield" would include the total discharge passing a given point, whether flowing in the channel or in the pervious material below and surrounding it.

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(Manuscript received July 26, 1946; presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 28, 1946; open for formal discussion until May 1, 1947.)

Transactions, American Geophysical Union Volume 27, Number VI . December 1946

REPORT OF COMMITTEE ON LAKES, 1945-46

S. T. Harding

The Committee on Lakes has continued during the past year without change in membership. While it has not had any directly sponsored committee program, some of its members have been active in the field of the Committee's subject matter.

Phil E. Church has continued his work on temperatures and other items in Lake Michigan. The results have been presented in publications of the University of Chicago and before technical societies. Church's paper at the Annual Meeting of 1945 indicated the scope of this work and some of its results. This was published in the Transactions of the American Geophysical Union [v. 27, pp. 109-110, 1946]. Ralf R. Wooley with Ray E. Marsell prepared a comprehensive bibliography on Great Salt Lake which was published in the same issue of the Transactions [pp. 103-110]. Church presented a further paper at the Annual Meeting of 1946.

During the War the Committee maintained its organization but did not attempt to carry on a program of Committee work. Now that such activities can be resumed, there are many subjects within the field of its subject matter which are desirable topics for its activities. Among those which have been suggested are: (1) Heat balance in both artificial and natural lakes; (2) form, distribution, and thickness of ice, particularly on the Great Lakes; (3) wind-driven and density currents, particularly in shallow water; and (4) stratification resulting from both temperature and chemical quality.

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(Manuscript received June 3, 1946; presented by title at the Twenty-Seventh Annual Meeting, Washington, D. C., May 29, 1946; open for formal discussion until May 1, 1947.)

Transactions, American Geophysical Union Volume 27, Number VI December 1946

DISCUSSION OF

"MOISTURE FACTOR IN CLIMATE" by C. W. THORNTHWAITE
[Trans., v. 27, pp. 41-48, 1946]

N. W. Cummings (San Bernardino, California, July 5, 1946)--Aside from any interest which the maps in Thornthwaite's paper may arouse, the last paragraph on page 42 invites attention because of its reference to a formula for computing evapotranspiration. Upon turning to the previous report therein mentioned [Trans., v. 26, pp. 686-693, 1945], one finds certain equations, but no explanation of the notation in which the equations are written. The omission is particularly unfortunate in view of the peculiar use that is made of ordinary algebraic symbols.

There is, however, a reference to still a third paper, to which I have as yet had only brief access. The general impression thus far received, is that evapotranspiration is expressed as a function of temperature alone, and that a total of six empirical constants is required. This impression naturally stimulates a desire to investigate the empirical equation with respect to precision and reliability, and to draw comparisons between results obtained by its use, and by the new direct use of the energy idea. It may be noted that the energy principle requires no empirical constants whatever, provided thermally insulated pan measurements are available. In this connection it should be noted, however, that an arbitrary value for the Bowen correction, and for back radiation difference, may need to be chosen when the requisite temperatures for determining these quantities rationally are not available. These corrections are small, however, and can be based on experience. Some unpublished work strongly indicates that when moisture supply is abundant the corrections are zero. The energy idea gives the moisture loss from an extended area; the procedure is not limited to results obtained from lysimeters.

In order that this and other comparisons may be drawn, it is necessary that a full explanation of Thornthwaite's procedure be made available. It would accordingly be useful if he would assemble in a single paper a statement of his equations, with an explanation of his notation and the manner of deriving the equations. Illustrative examples to show the method of application would be useful. Do the equations refer to lysimeter data or to losses from extended areas? A word regarding precision would be helpful. Thus in equation (2) on page 687 of the April 1945 report, he gives one of his constants to five figures. How many of them are intended to be significant?

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"OUR CHANGING CLIMATE" by J. B. KINCER
[Trans., v. 27, pp. 342-347, 1946]

Franklin I. Ryder (Minneapolis, Minnesota, October 17, 1946)--Kincer presents an interesting treatment of temperature trends. However, a comparison of temperature trends as outlined by the author to trends of precipitation and to consequent changes in lake levels might furnish additional testimony that our climate is changing.

Records of daily temperatures and precipitation have been maintained in the vicinity of Minneapolis, Minnesota, for approximately a century and a quarter. United States Army medical officers first recorded temperatures in 1819 at Fort Snelling, a military reservation adjacent to Minneapolis. Precipitation records for Minneapolis were begun in 1837. Total annual precipitation and yearly average temperatures for the state of Minnesota are available since 1890.

For the entire period of record, the mean annual temperatures and the total annual precipitation recorded at Minneapolis, and the average values for Minnesota were subjected to the ten-year moving summations, the device discussed by the author under "Temperature Trends." Figure 1 is a graph of these summations. Attention is called not only to the close agreement of the precipitation and temperature trends of the individual Weather Bureau Station at Minneapolis to those of the state as a whole but also to the inverse relation of temperature trend to precipitation trend. Temperature follows the pattern outlined by Kincer. As the trend of temperature declines, the trend of precipitation rises. Peaks of precipitation correspond to sags of temperature.

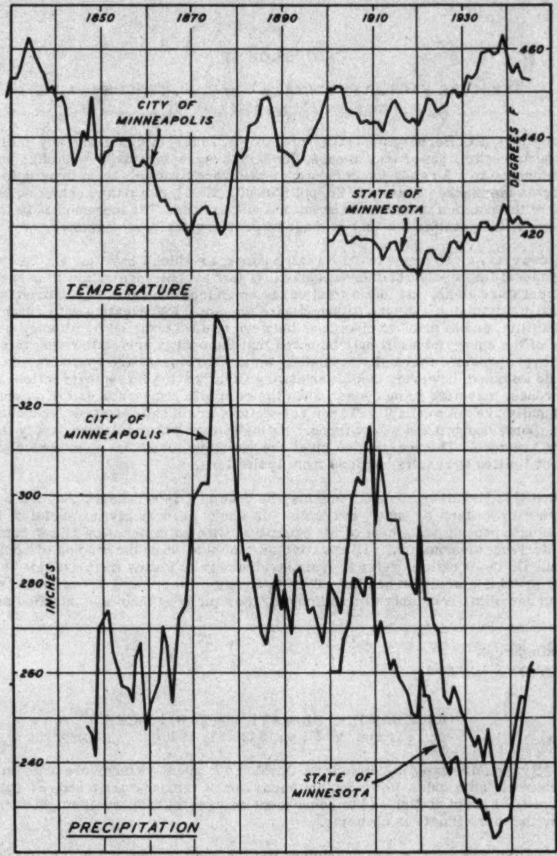

Fig. 1--Ten-year moving summations of temperature and average values of total annual precipitation recorded at Minneapolis, Minnesota

Twenty-five miles west of Minneapolis is Lake Minnetonka, with an area of 22 sq mi, a shore line of 100 miles, and an average depth of 40 feet. Annual high- and low-water levels of Lake Minnetonka since 1891 are plotted in Figure 2. Variation in levels of Lake Superior and the Great Salt Lake resembles the fluctuations of Lake Minnetonka. These lake levels vary directly as the trend of precipitation and inversely so to temperature. Such a relationship of lake levels to temperature and precipitation may be expected, since lake levels are directly proportional to rainfall and inversely proportional to evaporation [see "References" at end of discussion, MEYER, 1942]. Evaporation rates are dependent on temperature, wind, and humidity. As rainfall decreases, as temperature and evaporation rates remain static or increase, lake levels will be lowered.

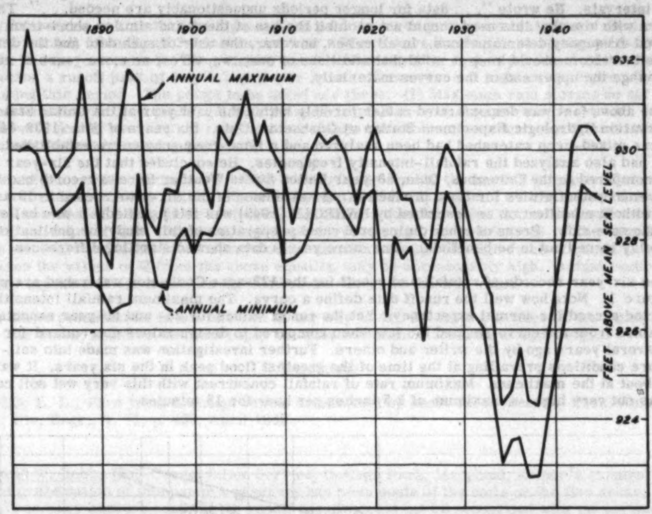

Fig. 2--Annual high- and low-water levels of Lake Minnetonka since 1891

Sunspots--constantly receiving attention of astronomers--are an indication of the amount of solar radiation reaching the Earth. Increased solar radiation and, incidentally, a larger number of sunspots [ANDREWS, 1937; DELUCY] appear to cause greater degree of evaporation from the Earth's surface and hence higher vapor content of the Earth's atmosphere, greater prevalence of clouds and rainfall. Sunspots were few in July 1933, increased to a peak in 1938, and dropped to a low in 1944. The next peak in sunspots may occur about six years hence. Cool, wet weather may be expected for the next six years. Sunspots, therefore, may be considered as indications of weather to come--the rate of change of "Our Changing Climate."

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"RUNOFF BEHAVIOR OF SMALL AGRICULTURAL WATERSHEDS UNDER VARIOUS LAND-USE PRACTICES" by HAROLD W. HOBBS

[Trans., v. 27, pp. 69-80, 1946]

[Corrigendum--On pages 75 and 76 of this paper, the figure on page 75 is Figure 7 with the title given on page 76. Similarly, the figure shown on page 76 is Figure 6, and should have the title given on page 75.]

L. L. Harrold (Soil Conservation Service, Coshocton, Ohio, received April 13, 1946--This paper presents some good data on flood peaks from agricultural watersheds under different land-use management. It was especially interesting to the writer because of his work along similar lines in recent years.

Hobbs uses records no longer than six years' duration. Some periods are for less than three years. Yet they are used to extend curves to frequencies of 10 to 20 years. He realized the inadequacy of the very short-term records for reliable determinations of values for greater recurrence intervals. He wrote ". . . data for longer periods unquestionably are needed. . ." The writer concurs with him that this need should not prohibit the use of these and similar short-term data for flood-frequency determinations. In all cases, however, the user of such data and the determinations therefrom should keep in mind that additions of one, two, three, or more years of record may change the upper end of the curves materially.

The above fact was demonstrated rather forcibly within the past year at the United States Soil Conservation Hydrologic Experiment Station at Coshocton, Ohio. Six years of data (1939-44) on a 122-acre mixed-crop watershed had been analyzed and a flood-frequency curve established. The writer had also analyzed the rainfall-intensity frequencies. He concluded that the six-year period (when compared to the Columbus, Ohio, 50-year United States Weather Bureau record) had higher than normal potentialities for flood production. An extension of the six-year record to 15 and 25 years without modification as described by HARROLD [1945] was felt justified. It was believed to be on the safe side. Press of other duties prevented preparation of this study for publication. This delay turned out to be beneficial. One more year's data showed startling differences.

The six-year records of rainfall and runoff for the 122-acre Coshocton watershed are plotted on Figure 1. Note how well the runoff data define a curve. The maximum rainfall intensities for the period exceed the normal expectancy. Yet the runoff values for 25- and 50-year expectancy determined from the curve seemed too low when compared to design values determined for this area several years ago by the writer and others. Further investigation was made into soil-moisture conditions prevailing at the time of the greatest flood peak in the six years. It was found to be about at the maximum. Maximum rate of rainfall concurrent with this very wet soil condition was not very high--a maximum of 2.5 inches per hour for 15 minutes.

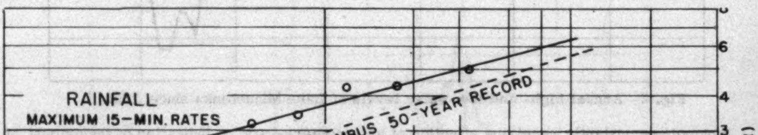

Fig. 1--Rainfall and runoff frequencies, watershed no. 10, 122 acres

At the end of 1945 another year's record was available. This seven-year record of runoff is also shown on Figure 1. Note that the maximum flood peak in the seven-year record is about three times as great as the largest peak in the six-year period. The frequency of this flood peak according to the curve defined by the six-year record would be somewhere above 1000 years. This seemed unreasonable. A curve defined by the seven-year record crosses over the rainfall curve. This also seems unreasonable. Somewhere between these two curves lies the true flood-frequency curve. Only time, and good, continuous records will determine its location.

It is interesting to note that the highest flood peak in seven years was caused by a maximum 15-minute rainfall intensity of 3.6 inches per hour. There were three rain storms greater than this in the seven-year period. The greatest rainfall intensity (five inches per hour) in the seven years caused a runoff peak of only 0.2 inch per hour. There were at least seven higher flood peaks during this period. The points to be noted are these: (1) Maximum rain storms do not always cause maximum flood peaks; (2) high rates of rainfall are not always concurrent with high soil moisture; and (3) peak-runoff rates can not always have the same recurrence interval as that of the rainfall intensity causing the runoff.

Users of the rational formula (Q = CIA) ordinarily determine the rainfall intensity (I) for the desired recurrence interval (10, 25, 50, or 100 years) and for the time of concentration of the watershed considered. This value is then multiplied by a coefficient for the wettest soil condition. The resultant value of Q is, therefore, high and safe for design. In some areas of the country extreme wet soil conditions do not always occur simultaneously with high rates of rainfall. In these cases the values of Q from the above equation may be unreasonably high. Actual records of runoff are expected to aid in evaluating flood peaks closer to the true value.

The above presentation is not intended in any way to detract from the value of the author's paper. The writer believes that this paper contributes much to the field of Hydrology.

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HARROLD, L. L., Flow from drainage basins determined by short-term records, Proc. Amer. Soc. Civ. Engr., v. 71, p. 433, April 1945.

Harold W. Hobbs (Soil Conservation Service, College Park, Maryland, Author's closure)--Since the presentation of this paper a resurvey has been made of the soils on the five areas. This became necessary because some of the runoff results could not be reconciled with the permeability and drainage conditions of the soils as originally mapped and described. The changes in classification determined are shown in Table 1.

Table 1--Changes in classification since original mapping and description of the soils

Area	Original soil	Drainage	Per cent area	New classification	Drainage	Per cent area
W-I	Beltsville loam	imperfect	48.7	Beltsville loam	imperfect	38.5
				Chillum gravelly loam	well	10.2
W-II	Beltsville loam	imperfect	33.1	Beltsville loam	imperfect	12.6
				Chillum loam	well	20.5
	Beltsville gravelly loam	imperfect	31.1	Chillum gravelly loam	well	31.1
W-V	Beltsville loam	imperfect	40	Chillum loam	well	40
	Beltsville gravelly loam	imperfect	60	Chillum gravelly loam	well	60
W-VI	Beltsville sandy loam	imperfect	47.7	Chillum sandy loam	well	47.7
W-VII	Beltsville sandy loam	imperfect	0.3	Chillum sandy loam	well	0.3

These new classifications indicate an increase in well-drained soils on W-I from 19.6 to 29.8 per cent (+ 10.2 per cent), on W-II from 35.8 to 87.4 per cent (+ 51.6 per cent), on W-V from zero to 100 per cent (+ 100 per cent), on W-VI from 6.5 to 54.2 per cent (+ 47.7 per cent) and on W-VII from 15.8 to 16.1 per cent (+ 0.3 per cent). [For revised soil maps of these areas, as well as design rates of runoff derived from runoff data from these and nine other areas, see "References" at the end of this discussion, HOBBS, 1946.] The reclassification of the soils makes major changes in the descriptions of the characteristics of W-II, W-V, and W-VI, and explains the runoff behavior of these areas (under the same or different practices) much more logically than before.

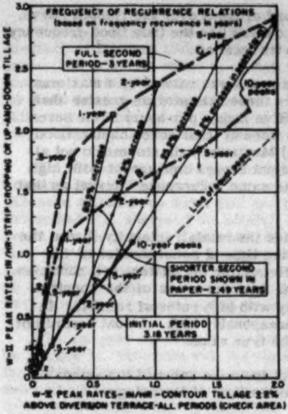

Fig. 1--Frequency of recurrence relation for initial and second comparative periods on W-II and W-V (both well-drained)

The frequency curves were used in the original paper to represent the runoff characteristics of the areas under various uses as well as for comparing areas under similar practices in the initial periods. These relationships can also be shown by plotting runoff values for various frequencies of recurrence against each other for comparable periods. This has been done for W-II and W-V in Figure 1. Curve A in this chart shows the comparison of frequencies for the initial period and Curve B the comparison for the second period of 2.49 years shown in the paper. Since the presentation of the paper, an additional half year of data has become available. The precipitation in this half year was 54 per cent in excess of normal (13.36 inches of rain fell in July 1945 alone). The additional record contributed 13 excessive rainfall intensities for ten-minute durations. This brought the rainfall frequency curve slightly above the modified Yarnell values for the second period as shown in the lower diagram in Figure 5 of the paper [Trans., v. 27, p. 74, 1946]. Curve C is a plotting of the frequency of recurrence relation of the runoff peaks for the full three-year second period. Figure 2 is a similar plotting of the frequency relationships between W-I (imperfectly drained) and W-II (well-drained) for the same three periods.

The author is impressed with the similarity of the B curves with the C curves in each of the two frequency of recurrence-relation plottings. It appears that the shorter second periods (B curves) brought out the trends in the relation even though they proved to be lower than the final curves for the longer three-year period. Since W-I and W-V were check areas and unchanged during both periods, it is possible to compare the increase in magnitude of various frequencies for W-II with each of these check areas independently. One-year peaks on W-II were increased 67.4 per cent when compared with W-I and 85.5 per cent when compared with W-V. The increase in two-year peaks on W-II is 55.4 per cent with respect to W-I and 52.2 per cent with respect to W-V. Five-year peaks increased 56.1 and 25.2 per cent, respectively, which values are more divergent, and the ten-year peaks show still greater divergence. A comparison of the check areas with one another for the same periods shows that the relative one-year frequency rates on W-V in the second period decreased 27.4 per cent compared with W-I, while the two-, five-, and ten-year peaks increased two, 19.7, and 39.1 per cent, respectively. This accounts for the divergences of W-II in

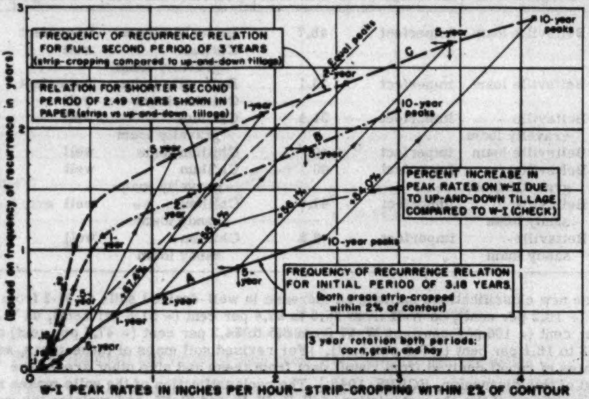

Fig. 2--Frequency of recurrence relationships between W-I (imperfectly drained) and W-II (well-drained) for the initial and second periods the one-, five-, and ten-year rates in comparison with W-I and W-V above. Apparently the channel-storage factor was less effective in reducing the higher peaks on W-V in the second period than in the initial period, when the peaks were relatively lower.

Harrold's suggestion that frequency curves derived from short-term records be used with caution is important. The main purpose of the paper was to characterize the runoff behavior of the several areas throughout the range in magnitudes represented by the data. However, circumstances may arise, as he points out, when it becomes necessary to extrapolate short-term data to flood peaks. In such cases two- and three-year records may have to be extended to ten-year frequencies and the five- and six-year records to 20-year values.

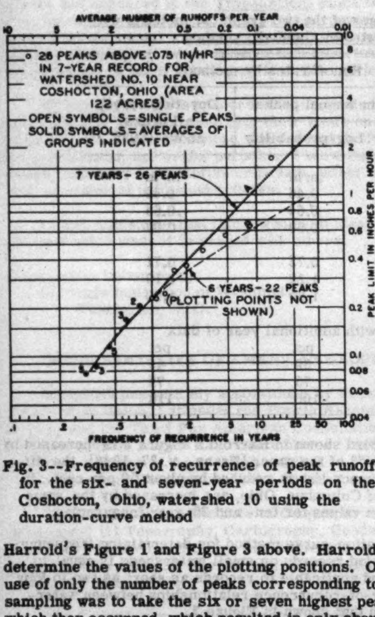

Fig. 3--Frequency of recurrence of peak runoff for the six- and seven-year periods on the Coshocton, Ohio, watershed 10 using the duration-curve method

The 1.72 inches per hour peak on watershed 10 at Coshocton, Ohio, in the seventh year of record appears to be an event caused by a set of conditions that will occur rather infrequently. Both the six- and seven-year records, unfortunately, have a poor distribution of values. Harrold supplied to the author the 26 peaks in the seven-year record which exceeded 0.075 inch per hour and included all the maximum annual values. When these were plotted by the duration-curve method on Hazen's modified log-probability paper (see Fig. 3) the upper 18 values were well represented by a straight line, A, which tends to curve downward among the lower eight values. The tendency is better demonstrated in curve B, which is the frequency relation for the first six years of record based on 22 values, but the plotting points are not shown. Additional years of record should supply some additional intermediate points between 1.72 and 0.563 inches per hour (or possibly even higher peaks), which may move A still higher. However, it is believed that it now is reasonably close to the ultimate line representing the characteristics of this watershed. Therefore, it would appear to be fairly safe to take frequencies-of-recurrence values of from ten to 25 years from the seven-year plotting. It is to be noted that the six years of record give very much lower values for the same frequencies.

At this point it is well to consider the differences in use of log-probability paper in Harrold's Figure 1 and Figure 3 above. Harrold multiplied the (2m - 1)/2n expression by 100 to determine the values of the plotting positions. On regular log-probability paper this permits the use of only the number of peaks corresponding to the length of record in years. His method of sampling was to take the six or seven highest peaks in the records without regard to the year in which they occurred, which resulted in only about half of the years being actually represented. In Figure 3, the author did not multiply by 100; consequently the plotting position is given in terms of the average number of times per year that the runoffs are equalled or exceeded, and makes possible the use of an unlimited number of values, so that all years can be represented in the sample, as well as a greater range in magnitude. Only a portion of Hazen's regular log-probability paper is thus needed (from 0.01 to 20 or 30). To facilitate plotting, this part was modified by expanding each interval to double size on the log-probability scale, and using three (instead of two) log bases of smaller size as the ordinate scale. This is the "modified" paper used in Figures 5, 8, 9, 10, and 11 of the paper and Figure 3 of the discussion.

By proper sampling of the data, however, the regular paper may be used over the full length. By taking the maximum annual peak for each year and the same plotting positions as those used by Harrold in Figure 1, plottings were made (but are not shown) for the six- and seven-year periods. A straight line was drawn among the points in each case and resulted in 0.245, 0.455, 0.64, and 0.90 inch per hour peak values for two-, five-, ten-, and 25-year frequencies for the six-year period and 0.315, 0.73, 1.12, and 1.80 inches per hour for the seven-year period. These are greatly different from the results shown by Harrold in Figure 1.

The reader may be interested in comparing the frequency values of the two graphical methods above for watershed No. 10 with the frequency values calculated from the six and seven maximum annual peaks by Gumbel's statistical method [GUMBEL, 1945 a]. Table 1 of that publication has been extended by W. D. Potter to cover the number of observations (n) from 15 to four, with the corresponding plotting positions. By using these values and Gumbel's special probability paper [GUMBEL, 1945 b], the six- and seven-year records furnished the values in Table 2, which also shows the graphical results. From a comparison of the increase in frequency rates for similar frequencies of recurrence, when the length of record is increased from six to seven years, the duration-curve method has the least percentage increase for five- and ten-year values and the annual peak-log-probability method the least for 25-year values. Gumbel's method had the greatest increase in all frequencies, which suggests that its limitation may be reached sooner as the length of the record period becomes shorter.

Table 2--Comparison of frequency values of the two graphical methods with the frequency values calculated by Gumbel's method

Length of record	Frequency of recurrence	Runoff rates by method		
		Maximum annual peaks		Duration curve, all peaks above 0.075
		Gumbel	Log-probability	
yrs	yrs	in/hr	in/hr	in/hr
6	5	0.50	0.46	0.49
6	10	0.64	0.64	0.64
6	25	0.81	0.90	0.87
7	5	1.05	0.73	0.71
7	10	1.43	1.12	1.10
7	25	1.91	1.80	1.90
	Increase in rates with additional year of data			
	pct	pct	pct	pct
	5	110	59	45
	10	124	75	72
	25	136	100	118

If the Columbus 50-year rainfall-intensity record shown in Harrold's Figure 1 is increased by eight or ten per cent for the reasons given on page 73 of the paper [Trans., v. 27, 1946], the difference between it and the Coshocton rainfall-frequency line is reduced by about 50 per cent. If Yarnell values [YARNELL, 1935] for the vicinity of Columbus, Ohio, are increased by the same amount, they are practically equal to the Coshocton values for ten- and 25-year frequencies.

In conclusion, the author believes that the duration-curve method for determining frequency of recurrence values of runoff peaks for short-period records on small watersheds is equal to any so far developed. It is the only reliable method applicable to records as short as two to four years. He is also of the opinion that the frequency-of-recurrence relationships between watersheds are best represented by diagrams similar to that shown in Figure 2.

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LETTERS TO EDITOR

PRESIDENT ADAMS COMMENTS ON DISCUSSIONS IN THE TRANSACTIONS

Probably most members of the Union have noted with satisfaction that some discussion of papers has appeared in the Transactions since the issuance of the Transactions as a bimonthly. It was, among other purposes, to provide a convenient medium for discussion that the change was made from an annual volume in parts to a bimonthly publication; and it is gratifying to realize that already advantage is being taken of this opportunity. Nonetheless, it is my feeling that this field of usefulness is not now being utilized to a sufficient extent by the members and other readers.

My principal object in addressing this note to you is to call to the attention of our readers the privilege they have for recording their views on matters of general interest in the various branches of geophysics. It is, of course, the earnest desire of all of us that our Transactions may serve an ever-increasing and useful purpose. I know that you, as Editor, will be happy to receive comments, including constructive criticism, either in the form of Letters to the Editor or in the form of discussions of published articles.

I hope, therefore, that those who have ideas will not hesitate to express them. A thought is of greatest value when it is shared with others!

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REPRESENTATIVE OF AMERICAN GEOPHYSICAL UNION AT CARACAS, VENEZUELA

In accordance with my appointment by President L. H. Adams as delegate of the American Geophysical Union, I attended the Fourth Assembly of the Pan American Institute of Geography and History and the Third Pan American Consultation on Cartography, which convened at Caracas, Venezuela, from August 22 to September 1, 1946. I am pleased to report briefly herewith regarding those features of the Meeting which it is believed will be of special interest and significance to the American Geophysical Union and its constituent Sections.

The Pan American Institute of Geography and History consists of four sections as follows: In Geography; (1) Topography, Cartography, Geodesy, and Geomorphology; and (2) Human Geography, Ethnology, Historical Biology, and Economic Geography; in History; (3) Pre-Columbia History, History of the Colonial Period, etc.; and (4) History of the Emancipation of the American Republics, History of Independence, etc.

The Commission on Cartography, created in 1941, has been studying inter-related problems of mapping, coming under six headings, namely; geodesy, topography and photogrammetry, hydrography, aeronautical charts, special maps and charts, and urban surveys. The work of the Commission replaces Section 1 of the Pan American Institute of Geography and History.

Recently, however, there has been a revision of the statutes with the view to delegating all subjects under Physical Geography to the Commission on Cartography, all other subjects on geography to the Commission on Geography, and all historical matters to the Commission on History. This year a Commission on Geography was organized, and a Commission on History was approved and undoubtedly will be organized in the near future.

The Commission on Cartography is engaged in annual consultations on matters that are both practical and cultural. Most people at all familiar with the subject are well aware of the need for much greater mapping data in the Americas, and this applies forcibly to the United States, although in a comparative sense we are recognized as leaders. The cultural value of well-managed cooperative consultations is enormous. It appears to me that the other interests of the Pan American Institute, namely, geography and history, are more cultural, although there are various means

of obtaining practical application on mutual problems of much concern. The work is well justified on either count.

The Commission on Cartography, designed to stimulate interest and action in the process of surveying and mapping in the Americas, has made significant progress in that direction. The first two consultations could not be expected to do more than lay the foundation for more concrete action at later meetings. The Caracas Consultation made distinct progress in adopting certain working standards and criteria of accuracy as a means of obtaining uniformity in the various areas. Obviously any international cooperation as regards processes and procedure in mapping can be arrived at only by operating according to uniform plans. Basic specifications and standards were adopted by the Committees on Geodesy, Topography and Photogrammetry, Hydrography, and Aeronautical Charts. The other committees under the Commission on Cartography were only recently organized.

Some 40 resolutions were approved, many of which had direct application to geophysical subjects of interest to the American Geophysical Union. Since these will eventually be available in published form, no attempt will be made to do more than cite a few of the most important.

One resolution called for a closer relationship between the Commissions of the Pan American Institute of Geography and History and the International Union of Geodesy and Geophysics for the dual purpose of exchanging work reports and personal representation at meetings. Other resolutions called for accelerated work projects for obtaining tidal, gravity, and magnetic observations and adequately processing the same. Of course, there have been numerous resolutions designed to augment all branches of cartographic work in the Western Hemisphere.

Already several Latin American countries have greatly accelerated their mapping programs, notably Argentina, Brazil, Peru, Colombia, Venezuela, and Mexico during the past two years, and now that there is public consciousness of the value of maps, it is believed that the work in other nations will soon be increased also.

The history of recent years has demonstrated conclusively that the peoples of the world must learn to get along with each other. We can learn to live together only by making personal contacts which are essential in all fields, professional and otherwise. It is through these ties that some of our common problems can be worked out.

It has been interesting to me at all these meetings to note a very general recognition not only of the importance of science and research but of the importance of cooperation and understanding among the scientific organizations of the world. By far the larger part of geophysical research and development concerns problems that are common to all, and the greatest good can come only from international understanding on these matters.

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NOTES AND PERSONALIA

NOTES

Autumn meeting of the National Academy of Sciences--The National Academy of Sciences held its autumn meeting of 1946 in Philadelphia, Pa., and Washington, D. C., October 20 to 23. The meeting was attended by representatives of academies and corresponding scientific societies of 21 of the 28 countries which were invited jointly by the National Academy of Sciences and the American Philosophical Society. The sessions were particularly devoted to the problems of international cooperation in science, with especial reference to astronomy, the various branches of geophysics, the use of high-speed computing machines, mineral resources, epidemic diseases, nutrition, plant diseases, publications and exchange of publications, international scientific unions and congresses, interchange of men of science, and UNESCO. Invited speakers presented summaries with reference to these subjects, and subsequent discussions were participated in by foreign representatives and others. On the evening of October 21, the Pilgrim Trust Lecture was presented in Philadelphia by Sir Henry Dale on the subject The Freedom of Science.

Following the meetings on October 23 was the Centenary Celebration of the Smithsonian Institution, which included a lecture by Dr. Matthew Stirling on the La Venta Culture of Southern Mexico, illustrated by motion pictures in color, and a reception.

Laboratory of Applied Geophysics and Geochemistry established at Pennsylvania State College--A laboratory of applied geophysics and geochemistry has recently been established at Pennsylvania State College under the direction of Sylvan J. Pirson, with a program of work including resident instruction in fundamentals and practical development research. It is believed that this is the first time that a course in geochemistry has been given in an American academic institution, though one was given in 1943 in the Graduate School of the Department of Agriculture. This school of thought has developed for some years in other countries, most notably in the U. S. S. R., where W. I. Vernadsky, A. E. Fersman, E. S. Federov, and others have laid extensive ground work in this field.

Bicentennial Program at Princeton University--The Bicentennial Program held at Princeton in the early days of October, 1946, had for its theme, Engineering and Human Affairs. It included a series of papers by invited speakers on the development of national resources.

International Council for the Exploration of the Sea--A meeting of the International Council for the Exploration of the Sea was held in Stockholm from August 12 to 17, 1946. J. R. Rymond of the Canadian Royal Museum of Zoology and Elmer Higgins of the United States Fish and Wildlife Service attended as observers. D. B. Finn, Director of the Fisheries Division, Food and Agriculture Organization of the United Nations, and Mary Sears of the Woods Hole Oceanographic Institution were present as guests. Naval services were represented by A. G. H. Wyatt, Hydrographer of the British Navy, and M. Dyevre, Director of the Hydrographic Service of the French Navy. The desirability of expanding the scope of the Council, and including the United States and Canada as member nations, was discussed. Such membership would involve participation not only in fisheries biology but in all of the different phases of oceanography.

Pacific Oceanic Biology Project--A Pacific Oceanic biology project, recommended at the Pacific Science Conference, has been instituted at the Woods Hole Oceanographic Institution by the Office of Naval Research. The following comprise the staff: Charles J. Fish, in charge, Gordon A. Riley, John C. Ayers, Rodney S. Notomi, Ruth von Arx, and Mary Curtis Cobb. Present quarters are in the Marine Biological Laboratory at Woods Hole.

Prospecting for resources in the U. S. S. R.--An extensive program of prospecting for minerals and the making of preliminary estimates of the findings has been entered upon by the U. S. S. R. About 1200 parties are to be placed in the field, many of whom are already at work. The plan includes 150 year-round expeditions, and it is expected that about one-third of all geophysicists and geologists in the U. S. S. R. will be involved in the program. Work is already in progress in the Baltic region, the Carpathian area, and elsewhere, and work will extend to the Urals, Siberia, and Central Asia.

Work of the Seismological Institute of the U. S. S. R.--N. A. Linden has made a study of deep-focus earthquakes, recorded between 1911 and 1944, with emphasis on propagation and reproducibility. E. A. Rozova has completed her studies on the focal depth of earthquakes in Central Asia. This has provided much data for the study of the core of the Earth. V. F. Bronchkovski has been investigating the cause of microseisms in Russia and has found that they are caused principally by strong westerly winds in Norway.

Origin of the Earth--The Institute of Theoretical Geophysics of the U. S. S. R. has developed a new meteoric theory of the formation of the Earth and other planets, based on astronomical data, on galactic rotation, and on the presence of dark matter in interstellar space. The work has been directed by O. I. Schmidt. V. V. Beloussev and Ronov are studying problems of geotectonic motions in relation to the history of the Earth.

Earthquakes in August, September, and October 1946--The series of West Indian earthquakes, which began with the destructive earthquake of August 4, 1946, off Samana Peninsula in the Dominican Republic [see Trans., v. 27, p. 762, 1946] continued during this period. Many small shocks were recorded from this region and two strong earthquakes occurred on September 25 and October 4 (see Table 1).

The Institute of Geology of the National University of Mexico reported that an earthquake was felt in Jaltipan, Veracruz, on September 2. Tacubaya seismograms showed an epicentral distance of 510 km and an origin time of $21^h52^m02^s$ U. T. It was reported on October 12 that the entire population of Niuafooa Island in the Tonga group had been evacuated because of daily earthquakes and a volcanic eruption. On October 8 an earthquake was felt in a wide area in the middle Mississippi drainage basin. The shock was felt in 30 counties in southeastern and central Missouri, 14 counties in western Illinois, and two counties in western Kentucky. It was felt strongest in Iron, Madison, and Wayne counties, Missouri. Typical of the descriptions of the earthquake in the epicentral region is the one by George Kemp of Saco, Missouri, who wrote that, "The earthquake was felt by all in the community. . . it was like an explosion of dynamite, then a roaring like thunder and seemed to raise the building. . . it lasted about eight to ten seconds." Although the earthquake was felt over almost 20,000 square miles and frightened many people, at no place was damage reported. With St. Louis, Florissant, and Cincinnati data, a preliminary epicenter was located at 37.5 N, 90.6 W; origin time $01^h12^m02^s.5$ U. T. This epicenter is on the southwest side of the St. Francois Mountains block in the northeastern Ozarks, but north of the New Madrid region.

As these data were being compiled, an earthquake was reported from the industrial districts of Uzbek and Kirghiz, Soviet Republics near Lake Aral, on November 3, 1946 (Local Time?). Official sources reported casualties and building damage in Namangan, Andizhan, and Fergana in Uzbek and in Dzhalal Abad in Kirghiz.

The preliminary epicenters in Tables 1 and 2 were determined by the United States Coast and Geodetic Survey and the Jesuit Seismological Association in cooperation with Science Service and a selected group of widely-scattered seismograph stations.

Table 1--United States Coast and Geodetic Survey epicenters

Date	Time U. T.	Epicenter		Remarks
		Lat.	Long.	
	h m s	°	°	
Sept. 12	15 16.9	25.5 N,	89 E	Northwest Bengal
Sept. 18	02 09.2	16 N,	101 W	Pacific Ocean, off southwest Mexico
Sept. 23	23 29.8	3 S,	144 E	North of New Guinea
Sept. 25	10 05.5	Aftershock of Dominican Republic quake		
Sept. 29	03 02.0	5 S,	154 E	Solomon Islands Region
Sept. 30	00 59.7	12.5 S,	76 W	West-central Peru, depth slightly less than 100 km
Oct. 2	04 45.9	51 N,	157 E	South of Kamchatka
Oct. 2	06 43 03	Aftershock of previous earthquake		
Oct. 4	14 45 26	19.3 N,	69 W	Off Samana Peninsula, Dominican Republic
Oct. 30	07 47.6	54 N,	164 W	South of Unimak Island, Aleutian Islands

Tab'e 2--Jesuit Seismological Association epicenters

Date	Time U. T.	Epicenter		Depth
		Lat.	Long.	
	h m s	°	°	km
Aug. 28	22 28 21	27.0 S,	63.5 W	550-600
Sept. 12	15 17 17	23.0 N,	92.0 E	
Sept. 13	18 59 17	52.8 N,	160.0 E	?
Sept. 18	02 09 09	16.0 N,	102.0 W	?

Swedish Expedition to the Mediterranean--An expedition to the Mediterranean was made by the Svenska H. B. Kommissionen on its research vessel Skagerak, beginning in April and covering a period of 2-1/2 months. The primary object of the cruise was to make preliminary tests in great depths of the coring apparatus to be used later in the Swedish Deep-Sea Expedition. W. Weibull's method of measuring, by echo-sounding, the distance from the sediment surface to the underlying substratum was also tested. A moderate-length tube (11 meters) was used in the core sampling and yielded cores from eight to ten meters in length to depths of 3600 meters, the maximum depth sampled. Much important data on volcanic activity over long periods were obtained. Echo-sounding experiments, made between Alger and the Tyrrhenian Sea, indicated a total thickness of the sediment, down to the reflecting layer, varying between about 450 and 2700 meters. Biological observations were made west of the Straits of Gibraltar and the coast of Portugal to and on Josephine Bank. The results obtained on this experimental cruise were found adequate for the proposed deep-sea work in the three oceans.

PERSONALIA

John C. Armstrong, formerly Captain in the Air Corps, has returned to the American Museum of Natural History in New York after wartime service in oceanographic research at the War Department in Washington and the Scripps Institution of Oceanography.

Jacob Bjerknes, Professor of Meteorology at the University of California at Los Angeles and AGU William Bowie Medalist in 1945, is now on sabbatical leave, working at the Geophysical Institute in Bergan, Norway.

Percy W. Bridgman, Professor of Physics at Harvard University, has been chosen by the Swedish Academy of Sciences as the 1946 recipient in the field of physics. The award was made specifically for Dr. Bridgeman's achievements in high-pressure physics.

James N. Carruthers, Oceanographer to the Hydrographic Department of the British Admiralty, is in the United States visiting oceanographic institutions. Following hostilities, he made an investigation of German military oceanography and is now engaged in postwar rehabilitation of scientific libraries and oceanographic research institutions. While in the United States, Dr. Carruthers is attached to the British Admiralty Delegation in Washington. His itinerary, before returning to England in late December, will include Woods Hole, La Jolla, Seattle, and various points in Canada.

Herbert G. Dorsey, Principal Electrical Engineer, retired from the U. S. Coast and Geodetic Survey on October 31, 1946. Since his entrance in the Survey in 1926, Dr. Dorsey has been intensely active in developing sonic methods for application to hydrographic surveying. Prior to 1926 he taught physics at the Universities of Maine and Florida, and Cornell University, and served as a research engineer for Western Electric Co., National Cash Register Co., Hammond Research Laboratory, and Submarine Signal Co.

Charles J. Fish, formerly Commander, USNR, and oceanographer in the Office of the Chief of Naval Operations, has joined the staff of the Woods Hole Oceanographic Institution. He has resigned as Professor in Charge of the Department of Zoology and Director of the Narragansett Marine Laboratory of Rhode Island State College, but will continue as consultant in Marine Biology.

R. W. Goranson of the Carnegie Institution of Washington has been detailed from the Geophysical Laboratory to the Department of Terrestrial Magnetism for a period of one year for the purpose of assisting and advising on two joint projects, (1) deep seismic prospecting of the Earth's crust and (2) development of special techniques for extreme pressures.

E. W. Lane has been appointed hydraulic consulting engineer with the Bureau of Reclamation with headquarters in Denver. Until recently, he was Professor of Hydraulic Engineering at the University of Iowa.

Donald B. MacMillan, who took his famed schooner, the Bowdoin, into the waters around Baffinland on his 24th Arctic Expedition this summer, brought back about 60 ornithological and other specimens. He is laying plans for another expedition in 1947 to the northern fringe of Greenland, expecting to reach within 11 degrees of the North Pole.

H. E. Merwin has recently retired from the staff of the Geophysical Laboratory, but has been given a temporary appointment as Research Associate of the Carnegie Institution of Washington to complete studies on the properties of liquids suitable for determination of refractive indices by the immersion method and to undertake identification and description of minerals and other compounds in various specimens of volcanic products.

Johan T. Ruud, Professor of Marine Biology at Oslo University and Director of the Norwegian Government Institute of Whaling Research, is now visiting oceanographic institutions in the United States. On November 10, 1946, he attended the International Whaling Conference in Washington as official representative of Norway. Dr. Ruud states that the Germans executed Jacob D. Sømme, Norwegian oceanographer, because of his activities in the Norwegian underground movement, and that Oscar Sund, another Norwegian oceanographer, was lost at sea when a vessel in which he was travelling off the west coast of Norway was destroyed by allied aircraft bombing.

Mary Sears, formerly Lieutenant Commander, USNR (W), in charge of the Oceanographic Unit at the Hydrographic Office in Washington, returned from Europe on October 28, 1946, and has resumed her work as planktonologist at the Woods Hole Oceanographic Institution. While in Europe she attended the meetings of the International Council for the Exploration of the Sea at Stockholm, and also continued studies on the "Dana" siphonophores at the Marinbiologisk Laboratorium.

H. R. Seiwell, formerly Lieutenant Colonel in the Corps of Engineers, has resumed his work at the Woods Hole Oceanographic Institution after service as Commanding Officer, Oceanographic and Beach Intelligence, European Theatre of Operations and the Pacific Ocean Area.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of October 25, 1946

The meeting was called to order at $14^{h}00^{m}$ in the Reading Room of the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C., President L. H. Adams presiding.

Present--Twenty-five persons were present, namely: L. H. Adams, K. H. Beij, Arthur Bevan, Ernst Cloos, Jno. A. Fleming, H. D. Harradon, H. F. Johnston, David G. Knapp, Earl Ingerson, W. D. Lambert, W. C. Lowdermilk, J. P. Marble, A. G. McNish, Leonard M. Murphy, F. W. Reichelderfer, Irwin Roman, J. F. Schairer, Waldo E. Smith, V. C. Stechschulte, H. T. Stetson, L. G. Straub, W. D. Sutcliffe, W. T. Thom, Jr., R. H. Weightman, and C. A. Whitten. The following were excused because of absence from the city or other reasons: W. H. Bucher, J. E. Church, J. A. Duerksen, R. E. Fuller, R. C. Gibbs, L. P. Hammett, C. R. Longwell, H. E. McComb, L. L. Nettleton, T. G. Thompson, C. W. Thornthwaite, and F. G. Wells.

Approval of Minutes--The minutes of the meeting of May 28, 1946, were published in the August issue of the Transactions [v. 27, no. 4, pp. 608-613, 1946]. No corrections were received, and the minutes were approved as published

General Secretary's Report

Executive Committee--The terms of W. W. Clark, L. P. Eisenhart, and W. W. Rubey as chairmen of Divisions of the National Research Council expired June 30, 1946, and L. P. Hammett, R. C. Gibbs, and Arthur Bevan have been appointed in their respective places, and thus become ex-officio members of the Executive Committee. Irwin Roman has taken over as acting Chairman of the Committee on Membership while G. W. Musgrave is on frequent and extended field trips. C. R. Longwell is acting Chairman of the Special Committee on National Welfare and Related Functions, replacing R. M. Field, who has resigned.

Personnel--Tresse C. Ford has been appointed to the office staff of the American Geophysical Union as secretary-stenographer, effective October 14, 1946. Marion Geoffroy, electromatic operator, has been promoted to the position of editorial assistant and electromatic operator; this action was approved by the Executive Committee.

Financial Report--The financial report for the year ending June 30, 1946, has been given the scrutiny of the Committee on Audit, which reported at this meeting. The report was published in the October issue of the Transactions [v. 27, no. 5, pp. 766-768, 1946].

The cash balance on October 1, 1946, in all funds of the Union was $16,980.90, which includes $11,827.80 of regular Union funds, $153.10 in the William Bowie Medal fund, and $5000 in the special fund left to the Union by Robert E. Horton to engage some of his former employees and to complete and publish some of his unfinished manuscripts. This fund was received through the National Research Council in early August. It was accepted, and the budget amended to include this item for expenditure during the next two or three years in payment for work done toward the completion and publication of Horton's manuscripts. Richard Van Vliet is now undertaking some of this work under the general supervision of the office of the Union and a special committee of the Section of Hydrology.

Since the report of June 30 to October 1, 1946, the total receipts (including the $5000 Horton fund and $1750 as the first-quarter payment of the Rockefeller Foundation) have been $9093.64. Total disbursements have been $5560.15. (Since October 1, the second-quarter payment of $1750 has been received from the Rockefeller Foundation.) Accounts receivable as of October 20 were just over $2000, and accounts payable, nil. In the accounts receivable were dues totaling $1556.70. Two hundred and forty-one members (including 34 new members) owe dues for 1946 totaling $1188.70. Forty-six members owe $368 for 1945 and 1946.

At the last meeting of the Executive Committee, it was approved, in the report of the Budget Committee, that the Union invest the payments of life memberships in long-term bonds. In line with the General Secretary's recommendation, it was approved that a total of about $2000 of the Union's funds should be placed in such bonds. It was agreed that, if possible, this amount should be placed in the Consolidated Fund of the National Academy of Sciences, if satisfactory arrangements could be worked out, including the withdrawal of funds. If this can not be done, the amount shall be invested in Series F Bonds of the Federal Government.

Membership--The membership as of October 23, 1946, was 2843. From May 23, 1946, to October 23, 1946, 119 new members were added to the rolls of the Union. In addition, there have been eight reinstatements. Nine members resigned during the same interval, and two deaths have been reported, Eliot G. Mears and Harry C. Dukes.

Publications--Since May 28, 1946, the Transactions of June and August have been published and distributed to members in good standing and to subscribers. The October issue has just been returned by the printer and will be ready for distribution before the end of the month.

With reference to the report on gravity and structure of the Caribbean Area, H. H. Hess, Chairman of the Committee on Geophysical and Geological Study of Ocean Basins, has pointed out that the work originally planned for the summer of 1939 will probably be done in the summer of 1947 with the aid of the funds from the Geological Society of America. This should probably then be a joint publication. The Executive Committee was favorable to this suggestion.

International Council of Scientific Unions, International Union of Geodesy and Geophysics, International Association of Geodesy--As American delegate, Walter D. Lambert attended meetings in England and France this summer, of all three bodies. (His reports are given in Appendices 1, 2, and 3.) A brief report was given on the American funds of the International Union of Geodesy and Geophysics; contribution of United States for adherence during 1944 and 1945 amounting to $7840.62 was received in October 1946, and balance now in hand is $22,042.88.

Meetings--Approval was given the plan of the South Pacific Regional Committee of the Section of Hydrology, under the Chairmanship of F. J. Veihmeyer, to hold a regional meeting at Pasadena, California, in February, 1947, in cooperation with the Western Snow Conference. Approval was also given the plan of the North Pacific Regional Committee of the Section of Hydrology, under the Chairmanship of John C. Stevens, to hold its meeting, postponed from April 1946, in April 1947, perhaps combining with the Northern Rocky Mountain Regional Committee. There was a further expression of the hope by the Executive Committee that such meetings will, when possible, be extended to include other Sections, or to be regional meetings of the Union as a whole.

The report of R. M. Field on the meetings held during the summer of the Commission on Continental and Oceanic Structure, and the Committee on the Social Value of the Earth Sciences, both of the International Union of Geodesy and Geophysics was abstracted, and approval given to the publication of a summary report in the Transactions, referring the matter for further consideration to the Editorial and Publication Committee.

The Executive Committee declined with regret the invitation of R. M. Field to hold an Executive Committee meeting in the Boston area in November, but wholeheartedly endorsed the idea for a later general regional meeting of the Union to be held in that area.

National Roster--The National Roster has published its first four vocational booklets. The fifth is planned to be one relating to geophysics. The plan for publication has been interrupted by uncertainty concerning the future of the National Roster, which is tied up with the Science Foundation Bill. The Executive Committee endorsed the program of publication of such booklets, and requested that the General Secretary do all he can to further the publication of the one relating to geophysics.

Tennessee Valley Branch--It was approved that the Union aid as may be necessary in establishing the Tennessee Valley Regional Branch of the Union, and authorized the General Secretary to make expenditures from budgeted funds as may be necessary for this purpose, but without considering this as a precedent.

Cooperation with American Association of Petroleum Geologists--It was approved that W. T. Thom, Jr. act as liaison between the Research Committee of the American Association of Petroleum Geologists and the Committee on Geophysical and Geological Study of Continents of the American Geophysical Union, as suggested by the Chairman of the Research Committee of the American Association of Petroleum Geologists.

Certificates of Membership--The suggestion that the AGU should issue Certificates of Membership to members who desire them was laid on the table.

Resolutions--The Resolutions passed at the last meeting have been sent out through the National Research Council as directed, except number 6 [see Trans. Amer. Geophys. Union, v. 27, no. 4, p. 590, 1946] relating to the Association of Geodesy of the International Union of Geodesy and Geophysics, which is awaiting the preparation of a list of officers of the Associations; and number 4 relating to climatological data, which has been withheld by the National Research Council because of its endorsement of a specific appropriation.

The matter of procedure on resolutions and the protest concerning the handling of two resolutions at the Twenty-Seventh Annual Meeting was deferred until the report of the Committee on Resolutions was heard.

Miscellaneous--Announcement was made of the establishment of the Laboratory of Applied Geophysics and Geochemistry at Pennsylvania State College; also the fact that an interesting paper by de Sitter on the situation in the coal-mining region of the Netherlands during the occupation. The paper was referred to the Editorial and Publication Committee for consideration for the Transactions.

Action on General Secretary's Report--The Report was accepted and approved.

Reports of Standing Committees

Nominations--Chairman Weightman presented the report on nomination and election procedures, which was adopted substantially as presented, in the form shown in Appendix 4. (Time schedules, and procedures for sections are given in Appendices 5 and 6.

Editorial and Publication--Chairman Fleming reported briefly on meetings of the Committee on June 20 and October 11, 1946, noting the recommendation of the Committee that the Transactions carry discreet and dignified advertising. Action on this was deferred pending the report of the Committee on Membership that bears to some extent on the matter.

Membership--Acting Chairman Roman presented the following proposals on advertising and corporation memberships, without recommendation: (1) Advertising should be restricted to the back pages of each issue and should be such as not to conflict with or detract from the list of corporation members to be printed in the front pages of each issue; (2) display advertising shall not be accepted; (3) a simple listing, under suitable headings, shall contain the name and address of a company or its representatives. No special messages shall be included. An advertiser may be listed under as many headings as he wishes, the rate to be determined uniformly on the basis of a unit consisting of one entry in one issue; (4) professional cards approximately one inch high and two and a half inches wide may contain the name and address of the advertiser, his trade mark, his line of activity, and announcements of special equipment. A card may contain more than one basic space but shall have a height and width each of which is approximately an integral multiple of the basic value. The unit of charge for such cards shall be insertion in one issue for one basic card space. Except for plates to be furnished by the advertiser, professional cards shall be in the same type font as that used in the Transactions. Plates may contain special designs of trade mark and special type fonts, but shall not include special displays not specifically identifying the advertiser. Members of an organization may advertise in addition to the organization card, and may show the organization name as a minor item, but no advertiser shall use more than one card in one issue of the Transactions.

On Roman's motion, it was approved that a special committee of five be appointed to consider the matter of finances (as suggested by the Report of the Committee on Budget) [see v. 27, no. 4, p. 612, 1946], and advertising in the Transactions, and report back to the Executive Committee.

Acting Chairman Roman also noted the net growth in membership of 116 since the last report on May 28, 1946. He mentioned that 33 applications are in hand for processing soon.

The name of F. A. Vening Meinesz was presented for consideration for Corresponding Member, as recommended by the Committee on Membership. This nomination was approved and Vening Meinesz was elected a Corresponding Member.

The Committee on Membership also recommended that the Executive Committee consider the matter of formal affiliation with the American Association for the Advancement of Science inasmuch

as such affiliation might be helpful in bringing and keeping the name of the Union before prospective members that otherwise might not be reminded of its existence. It was approved that this consideration be given, both with respect to our relationship with the National Research Council, our parent organization, and the American Association for the Advancement of Science.

Meetings--Chairman Marble recommended that the Twenty-Eighth Annual Meeting be set for April 28 to 30, 1947, in Washington, D. C. This was approved. He reported further as shown in Appendix 7.

Audit--Chairman McNish stated that the report of the Committee on Audit has been published in the October issue of the Transactions [v. 27, no. 5, pp. 766-768, 1946]. The report was approved.

Reports of Special Committees

National Welfare and Related Functions--Acting Chairman Longwell was unable to be present. His report (see Appendix 8) was read and approved, and the present Committee declared dissolved, and authority given for the appointment of a new Committee as provided by the report.

Resolutions--Chairman Ingerson recommended procedure for the handling of resolutions as shown in Appendix 9. This was approved. With regard to two resolutions of H. C. Mitchell not acted upon favorably at the time of the Twenty-Seventh Annual Meeting, it was suggested that Mitchell be invited to present these at the Twenty-Eighth Annual Meeting if he desires.

Geophysical and Geological Study of Continents--Chairman Thom reported briefly that progress is being made on the revision of the basement complex map of the United States.

Cosmic-Terrestrial Relationships--Chairman Stetson made no formal report, but only a brief report that progress is being made.

Affiliation with the American Geological Institute--Chairman Thom reported that the two committees appointed at the time of the conference last year would soon report, and that then a more definite statement could be made.

Committee on the Metric System--President Adams announced the appointment of the following Committee: Lewis V. Judson, Chairman; H. R. Edmonston; H. H. Howe; C. E. Jacob; and A. G. McNish, representing all Sections.

Section Matters

Terrestrial Magnetism and Electricity--President Johnston reported that word had come of the availability of the funds for the Alaska Magnetic Observatory, and that the United States Coast and Geodetic Survey plan to push this project as much as possible.

Hydrology--Secretary Beij expressed the desire of the Section of Hydrology to cooperate with all other Sections and the Union as a whole in the matter of holding regional meetings.

New Business

General Secretary Fleming reported briefly concerning the recent meetings of the National Academy of Sciences and the American Philosophical Society, and the grant made by the Rockefeller Foundation and the Carnegie Corporation to bring foreign scientists to the meetings. He also mentioned the success of the International Union, and the fear in some quarters that UNESCO might infringe upon their autonomy.

The meeting adjourned at $17^{h}55^{m}$.

Jno. A. Fleming,
General Secretary
Waldo E. Smith,
Executive Secretary

APPENDIX 1--GENERAL ASSEMBLY OF THE INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

Walter D. Lambert

The first General Assembly of the International Council of Scientific Unions since the War was held at London on July 22-24, 1946, in the rooms of the Royal Society, which acted as host. Twenty-one countries and various international unions and other scientific bodies were represented by about 70 delegates. H. R. Kruyt of the Netherlands presided.

Much routine business was transacted and there was a good deal of informal discussion about the activities of the various international scientific unions and the possibilities of forming new unions to cover sciences not now covered by existing unions. A resolution regarding the use of atomic energy and the responsibility of scientists in regard to its use was discussed at length and adopted after amendment.

Perhaps the most important business before the meeting was the discussion of a working agreement with UNESCO (United Nations Educational, Scientific, and Cultural Organization). As an international body with an ample budget and with diplomatic privileges UNESCO will be in a position to aid international scientific work in many ways, for instance in the collection of national dues to international organizations, the procuring of passports and visas for scientists attending international meetings, financial aid in meeting the expenses of the necessary travel, clerical, and secretarial aid at and between international meetings, and the support of permanent international scientific enterprises, such as the International Latitude Service.

A preliminary draft agreement was discussed, line by line, and adopted after several amendments had been made, all approved by a representative of UNESCO, Joseph Needham, who was in attendance throughout the meeting. On acceptance by UNESCO, which is expected to occur soon after UNESCO perfects its own organization, presumably before the end of the current year, the details of the agreement will be made public.

Officers elected for the coming triennial period were: President, Jno. A. Fleming of Washington; Vice Presidents, B. Němec of Prague and Emile Borel of Paris; General Secretary, F. J. M. Stratton of Cambridge, England (reelected); Members of the Executive Committee, J. N. Mukherjee of New Delhi and H. Solberg of Oslo.

Provision was made for annual instead of triennial meetings of the Executive Committee. On the invitation of Denmark, the next meeting of the Council will be held in 1949 at Copenhagen.

APPENDIX 2--EXTRAORDINARY GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

Walter D. Lambert

An extraordinary general assembly of the International Union of Geodesy and Geophysics was held at Cambridge, England, July 29-August 2, 1946. This meeting had been called by the Executive Committee of the Union meeting at Oxford, England, in December 1945. The purpose of both meetings was the reactivation and reorganization after the War of the work of the Union. Sixteen countries were represented. The delegates were housed, a few each, at some of the various colleges of the University.

In the absence of the President, B. Helland-Hansen of Norway, detained by ill health, N. E. Nörlund of Denmark presided.

The principal business before the meeting was the preparation of new statutes and by-laws. The statutes and by-laws as adopted follow the general lines of the drafts prepared by the former General Secretary, H. S. J. L. Winterbotham, at the request of the Oxford meeting of the Executive Committee.

The statutes are briefer and more general than the previous ones, and much of the detail is left to the by-laws. The Committee on Administration and Finance becomes the Council, with somewhat greater powers and more clearly defined responsibilities than its predecessor. The intention was to separate administrative and financial matters from questions of scientific policy, which are the special province of the Executive Committee. This Committee is composed of the

President, two Vice Presidents elected as such (a new provision), the General Secretary, and the Presidents of Associations.

In the former statutes a scale of national dues was provided based on the population of the adhering countries. This method of assessment had long been found unworkable and many exceptions had been allowed in practice. The Assembly adopted a free-will basis, each nation choosing its own place on the scale, subject to the proviso that a manifestly unsuitable choice may be disallowed. The unit of contribution (the scale of contributions runs from one to eight units) was reduced from 1500 Swiss gold francs, equivalent to about 121 pounds sterling at current rates, to 100 pounds for the present, with an upper limit of 150 pounds.

It was agreed that the meeting was sufficiently representative for its decisions to be considered as binding. Accordingly, these statutes and by-laws will be considered as in effect from January 1, 1947, unless before that time objections are received from more than one-third of the adhering countries.

Under the new statutes Helland-Hansen, elected at Oxford, vice D. La Cour, deceased, was confirmed as President. H. S. J. L. Winterbotham of England and N. E. Nörlund of Denmark were elected Vice Presidents, and J. M. Stagg of England was confirmed as General Secretary.

The draft agreement between UNESCO (United Nations Educational, Scientific, and Cultural Organization) and the International Council of Scientific Unions was approved.

F. A. Vening Meinesz, former President of the Association of Geodesy, was designated as the representative of the Union at the third Pan-American Consultation on Cartography to be held at Caracas, Venezuela, in August, and provision was made for the payment of his expenses.

The next meeting of the Union will be held in Norway in 1948.

APPENDIX 3--MEETING OF THE PERMANENT COMMISSION OF THE INTERNATIONAL ASSOCIATION OF GEODESY

Walter D. Lambert

Early in June a meeting of the Permanent Commission of the International Association of Geodesy was called by the "Bureau" of the Association and the date set for August 5-7, 1946, following close upon the Cambridge meeting of the parent organization, the International Union of Geodesy and Geophysics. The place of meeting originally designated was the office of the Association, 19 rue Auber, Paris, but the meetings were actually held in larger quarters in one of the buildings of the newly established Institut Géographique National of France, formerly a city mansion (hôtel) of the historic de Rohan family.

Seventeen countries were represented, including two South American countries, Argentina and Peru. The Permanent Commission is an organization modeled after an organization of similar name in the old International Geodetic Association (Internationale Erdmessung) as it existed before World War I. The functions of the Permanent Commission are mainly to deal with administrative and financial matters, so that it corresponds rather closely to the newly-established Council of the Union of Geodesy and Geophysics. Because of its representative character and because of the urgency of the situation, since no meeting of the Association will be held until 1948, the meeting felt itself justified in assuming the character of an extraordinary general assembly of the Association and in making decisions accordingly.

Much attention was given to the budget and to the publications of the Association. It was decided to try the experiment of limiting the free distribution of publications and of asking payment in many more cases than previously.

Certain tables published by the Association were found to be out of print and ordered reprinted. The Bibliography of Geodesy was ordered continued and sold as far as possible, instead of being given free. The Bulletin Géodésique was ordered continued as a quarterly, a new series to begin with the number for July, 1946. An index for the old series was ordered prepared. An attempt will be made to increase the subscription list of the Bulletin.

It was decided to print a set of tables, prepared by P. Lejay, for the topographic and isostatic reduction of gravity, including the indirect effect. The purpose of the publication is to include all necessary tables in one volume and thus facilitate the reduction of gravity stations throughout the world by one uniform method.

It was felt that the national reports, hitherto published triennially in connection with the general assemblies, were of very unequal value and often of little real interest outside the country of their origin. It was therefore ordered that these reports be discontinued and that instead data on the subjects of the reports (operations, results, instruments, methods, etc.) be collected from the various countries through the Secretary's office and summarized by a competent reporter.

An annual subsidy to the International Latitude Service and a special subsidy for the publication of results, both matching those of the International Astronomical Union, were ordered. The continued publication of the results of the International Longitude Campaign of 1933 but with fewer details, as tentatively arranged with the General Secretary of the Astronomical Union, was also ordered, and the usual subsidies to the Bureau de l'Heure (paid through the Union) and to the Isostatic Institute at Helsinki were continued.

The most drastic change in organization that was made affected both the Executive Committee and the scientific committees.

The scientific committees had become so numerous and made such demands on the time of the delegates at assemblies, with important committee meetings usually conflicting with one another and demanding the presence of the same delegate at several places at the same time, that some remedy was urgently needed. Accordingly, it was decided to group the committees into five sections or groups, each under a general chairman. The groups or sections adopted were: (1) Triangulation; (2) Precise Leveling; (3) Geodetic Astronomy; (4) Gravimetry; and (5) Geoid. Each of the 12 reporters on various subjects such as bases, leveling, deflections, gravity, and earth tides would be attached to an appropriate section.

It was ordered that the Executive Committee consist of the President, the Vice Presidents, the Secretary, and the five Chairmen of Sections. The Second Vice President, as before, is to be chosen from the country where the next General Assembly is to be held. The President and the General Secretary were held ineligible for the position of Chairman of a Section. The meeting then proceeded to elect in accordance with this scheme. It was considered that P. Tardi had already been elected Secretary by mail vote of the Permanent Commission, so his election was merely confirmed. The other elections resulted as follows, all persons being elected to serve until the end of the 1948 General Assembly of the Association: President, Walter D. Lambert, United States of America; Vice Presidents, C. F. Baeschlin, Switzerland, and H. S. Jelstrup, Norway; Chairmen of Sections and ex-officio members of the Executive Committee: (1) Triangulation, Pierre Jacquinet, France; (2) Leveling, Jean Vignal, France; (3) Geodetic Astronomy, N. E. Nörlund, Denmark; (4) Gravimetry, F. A. Vening Meinesz, Netherlands; (5) Geoid, J. de Graaff Hunter, Great Britain.

The position of Associate Secretary was also created, in accordance with the recommendation of the Oxford meeting of the Executive Committee of the Union (December, 1945), and G. R. Laclavère was elected Associate Secretary. He was given authority to draw checks, if necessary, on the bank account of the Association at the Comptoir National d'Escompte of Paris.

The final day of the Meeting was devoted chiefly to a project for the unification of the triangulation, a subject that had long been under consideration by the Association. The possibility of making progress towards unification arises from the fact that the triangulation of Central Europe is being readjusted and unified by a team of German geodesists and computers working at Bamberg under Allied military control. This readjustment and unification could obviously be extended to countries adjoining the Central European area and finally to the entire continent. This would, of course, require the cooperation of the nations whose territory would be covered by the extensions of the adjustment in various directions.

This point of view was explained to the meeting by Floyd W. Hough of the United States Army Map Service. An animated discussion ensued, in which the objections to the project, military, political, scientific, and sentimental, were brought out. It was noted that part of the European area was already covered by a rather accurate readjustment under the auspices of the Baltic Geodetic Commission.

The Association naturally wished to avoid involvement in questions of a military and political nature and so finally voted to establish a special committee on the European triangulation, to consider only the scientific and technical aspects of the problem. It would be formed under the direction of Chairman of the Triangulation Section, Pierre Jacquinet. Since the problems to be considered are scientific and technical and not territorial, membership in the committee will not be confined to the nations of Europe but each member country of the Association will be invited to designate a representative on the Committee. After the Committee is organized the question of representation of countries not members of the Association can be considered by the Committee itself. Notices of this decision and requests to designate a representative have already been sent out to member countries.

APPENDIX 4--REPORT OF STANDING COMMITTEE ON NOMINATIONS, INCLUDING NOMINATION AND ELECTION PROCEDURE FOR THE UNION AS APPROVED BY THE EXECUTIVE COMMITTEE ON OCTOBER 25, 1946

R. H. Weightman, Chairman
C. A. Heiland W. W. Rubey
J. B. Macelwane F. J. Veihmeyer

Your Committee has given further attention to the matter of nominations and election of Union (as distinguished from Section) officers. The questionnaire published in the Transactions [v. 27, no. 4, p. 613] brought forth only 34 replies (slightly over one per cent) from a membership of 2800. The number is so small that it can hardly be accepted as representative of Union opinion. There are two principal questions on which there are differences of opinion, namely: (1) The number of nominees, and (2) should nominations be requested of the entire membership. The only information we have on these questions stems from discussion at the meeting of the Executive Committee on January 25, 1946, discussions and questionnaire filled out by members of the Executive Committee on May 28, and responses to the questionnaire published in the Transactions. The results of the two questionnaires are given below:

	Executive Committee May 28, 1946 (28 voting)	Questionnaire in Transactions (34 voting)
(1) More than one nominee	17	20
(2) More than two nominees	--	3
(3) Nominations by entire membership	1	14
(4) Nominations by committee	27	20

It was adopted (1) that nominations be initiated by a small Nominating Committee consisting of three or five members, appointed by the President; (2) that at least two persons be nominated for each of the offices of President, Vice-President, and General Secretary; (3) that such nominations then be submitted by the Nominating Committee to the Executive Committee, which body may accept the report, or add other nominees for such offices. It will then proceed to select by secret ballot not less than two official nominees for each office; (4) that such nominations then be announced to the membership, sufficient time being provided before election to permit further nominations by petition when signed by one per cent of entire membership, it being mandatory that nominations by petition be added to the official nominations; (5) that ballots containing official nominations and those submitted by petition be mailed to the active membership and that such ballots, postmarked before a specified date, be marked and forwarded by the membership to the General Secretary; (6) that the General Secretary within ten days after the specified date, turn over all such ballots for tallying to a Committee of Tellers consisting of one member selected from each of the eight sections and one member from the Executive Committee; (7) that the said Committee of Tellers make report to the General Secretary within ten days, showing the result of the ballot; (8) that a plurality of votes cast shall elect; (9) that consent of each candidate is to be obtained before placing his name on the ballot; and (10) that the Sections be urged to adopt similar procedure.

APPENDIX 5--TIME SCHEDULE FOR NOMINATIONS AND ELECTIONS

The office of the Union has worked out the following time schedule in cooperation with the Chairman of the Committee on Nominations to provide maximum use of the Transactions in the nomination and election procedure. This will be the normal schedule, though as noted below, the first date will not apply this year.

November 10--The Committee on Nominations will present their report to the Executive Committee at a meeting to be held in the fall preceding election years, not later than November 10. The

Executive Committee will perform its functions under item (3) of the procedure [see Appendix 4], following which the names of "official nominees" will be printed in the December issue of the Transactions. (It is expected that Sections will adopt procedures that will coordinate in time schedule, permit of publication of "official nominees" in the December issue of the Transactions, and thereafter follow the time schedule herein shown.)

February 1-10--Further nominations by petition must be received in the office of AGU by February 10 (or by February 1, if written consent of candidate has not previously been secured).

March 1--Ballots carrying the official nominations, to which will be added those received by petition, will be mailed to members not later than March 1. Brief biographical sketches relating to each nominee (Union and Sections), will accompany, but not be a part of, the ballot.

March 31--Balloting will close on March 31. Ballots must be postmarked not later than that date and be received by the General Secretary not later than April 4 in order to be counted.

Special note--This year, because of the lateness of the time, there will need to be deviation from the time schedule above. The Transactions of December cannot be used to publish the names of the official nominees, as these Transactions go to press November 25, notice of official nominees for Union and for Section offices will be mailed to each member in the latter part of December. The tentative plan is to hold a meeting of the Executive Committee of the Union on about November 29 to fulfill the provisions of item (3) in the procedure. Official nominations for Sections with consent of candidates should be in the office of the Union by this date (November 29). From February 1 on we plan to maintain the above schedule.

APPENDIX 6--PROCEDURE FOR THE NOMINATION AND ELECTION OF OFFICERS OF THE SECTIONS

Foreword--In general, the nomination and election procedures of the Sections follow closely the nomination and election procedure set up for Union officers [see Appendix 4], and their time schedules are such that they fit into the time schedule set for the nomination and election of Union officers [see Appendix 5]. The Committees on Nomination of all Sections refer their reports to the office of the Union for publication without reviewing action by the relatively small Executive Committees of the Sections. The greatest deviation from the procedure for the Union is in the instance of the Section of Hydrology, where suggestions for nominees from the members proceed to January 15, and there is normally to be no publishing of the list of "official nominees" in the December issue of the Transactions.

Elections for all Sections are held triennially, as in the case of the Union. The ballot to be mailed in late February 1947, will cover the election of officers of the Union and of the Sections.

(a) Section of Geodesy--(1) Nominations will be initiated by a small Committee on Nominations consisting of three members appointed by the President of the Section. (2) At least two persons shall be nominated for each of the offices of President, Vice-president, and Secretary; the Committee on Nominations obtaining the consent of each candidate before submitting the nominations to the office of the Union. (3) Nominations will be announced to the membership, sufficient time being provided before election to permit further nominations by petition. The petition shall be signed by at least ten members affiliated with the Section, and the consent of each candidate shall be obtained before the petition is submitted to the office of the Union. It is mandatory that nominations by petition be added to the official nominations. (4) Ballots containing official nominations and those submitted by petition shall be mailed to the active membership, and such ballots, postmarked before a specified date, shall be marked and forwarded by the membership to the office of the Union. (5) The office of the Union, within ten days after the specified date shall turn over all such ballots for tallying to the Union Committee of Tellers. (6) The said Committee of Tellers shall make a report to the office of the Union within ten days, showing the results of the ballot. (7) A plurality of votes cast shall elect.

The Committee on Nominations for the Section of Geodesy, for the officers to be elected in 1947 consists of: R. M. Wilson, Chairman; W. D. Lambert; and C. H. Swick.

Walter D. Sutcliffe, President,
Section of Geodesy

(b) Section of Seismology--(1) A Committee on Nominations shall be appointed by the President at the Annual Meeting preceding elections and shall be composed of at least three members including the Chairman. (2) Two or more nominations for each office shall be made by the Committee. Consent of the nominees shall then be obtained before placing their names on the ballot. (3) Nominations shall be forwarded to the General Secretary through the Section Secretary for inclusion in the general Union ballot. (4) Nomination by petition of any six members affiliated with the Section shall also be included on the ballot if authorized by nominee. Petitions to be acted on shall be sent to either some member of the Committee on Nominations or to the Section Secretary. The Executive Committee of the Section shall be empowered to raise the required number of petitioners in case six becomes less than one per cent of Section membership. (5) Ballots shall be counted by a Committee of Tellers of the Union which will include a representative of the Section of Seismology according to the procedure approved by the Executive Committee of the Union. (6) The nominee receiving the largest number of ballots for each office shall be declared elected. (7) Changes in nominating procedure may be adopted at any Annual Meeting.

Committee on Nominations,
R. R. Bodle, Chairman
J. B. Macelwane
H. H. Neuberger

(c) Section of Meteorology--(1) There shall be a Committee on Nominations consisting of three to five members, appointed by the Executive Committee of the Section, except that this year the Committee will be appointed by the President, as has been customary in the past. (2) The number of nominees submitted for each office will be optional with the Committee on Nominations. (3) The Committee on Nominations will arrange for disseminating nominations to members in sufficient time to permit further nominations by petition. It will be mandatory that nominations by petition be added to the official nominations and it shall be indicated on the ballot that such nominations are by petition. These petitions must be signed by at least 25 members and be forwarded to the office of the Union with consent of the candidates. (4) Ballots containing the names of all nominees will be mailed to members of the Section, be properly marked by the members, and shall be forwarded to the General Secretary of the Union. They must be postmarked not later than a specified date. (5) The ballots shall be counted by the Committee of Tellers of the Union and the results made known to the membership in accordance with Union procedures set out in the Transactions of December 1946. (6) A plurality of votes cast shall elect. (7) The time schedule pertaining to nominations and elections shall be in accordance with the notice published in the Transactions of December 1946, it being noted that special provision is made for a special time schedule this year.

The Committee on Nominations of the Section of Meteorology consists of C. W. Thornthwaite, Chairman; Robert D. Fletcher; and Robert G. Stone.

F. W. Reichelderfer, President,
Section of Meteorology

(d) Section of Terrestrial Magnetism and Electricity--(1) Nominations for office in this Section are to be initiated by a Committee on Nominations consisting of five members selected by the Executive Committee of the Section. (2) At least two persons are to be nominated for each of the offices of President, Vice-president, and Secretary. (3) The Committee on Nominations shall arrange for announcing the official nominations to the membership, sufficient time being provided before election to permit further nominations by petition when signed by one per cent of the members affiliated with the Section and accompanied by consent of the nominee (the actual number required by this provision will be published with the announcement of the official nominations), it being mandatory that nominations by petition be added to the official nominations. (4) Ballots containing official nominations and those submitted by petition are to be mailed to the active membership, and such ballots are to be marked and forwarded by the membership (postmarked before a specified date) to the General Secretary of the Union. (5) The ballots are to be counted by the Committee of Tellers of the Union. (6) A plurality of votes cast shall elect. (7) The consent of each candidate is to be obtained before placing his name on the ballot. (8) The time schedule shall be adjusted to dovetail with the time schedule adopted for the election of officers of the Union.

The Committee on Nominations of the Section of Terrestrial Magnetism and Electricity for officers to be elected in 1947 consists of O. H. Gish, Chairman; H. D. Harradon; Frederick W. Lee; Elliott B. Roberts; and Harlan T. Stetson.

David G. Knapp, Secretary,
Section of Terrestrial Magnetism
and Electricity

(e) Section of Oceanography--(1) Nominations will be initiated by a small Committee on Nominations consisting of three or five members, appointed by the President of the Section. (2) At least two persons shall be nominated for each of the offices of President, Vice-president, and Secretary; the Committee on Nominations obtaining the consent of each candidate before submitting the nominations to the office of the Union. (3) Nominations will be announced to the membership, sufficient time being provided before election to permit further nominations by petition when signed by ten members affiliated with the Section, it being mandatory that nominations by petition be added to the official nominations. (4) Ballots containing official nominations and those submitted by petition shall be mailed to the active membership, and such ballots, postmarked before a specified date, shall be marked and forwarded by the membership to the office of the Union. (5) The office of the Union, within ten days after the specified date, shall turn over all such ballots for tallying to a Committee of Tellers, one member of which shall be selected from the Section of Oceanography. (6) The said Committee of Tellers shall make a report to the office of the Union within ten days, showing the result of the ballot. (7) A plurality of votes cast shall elect.

The Committee on Nominations for the Section of Oceanography for the officers to be elected in 1947 consists of H. A. Marmer, Chairman; G. Medina; and Martin A. Mason.

L. P. Disney, Secretary,
Section of Oceanography

(f) Section of Volcanology--The procedure will be identical with that established for the Union (see Appendix 4) except that Item (3) of the procedure will be eliminated, and the Committee on Nominations will transmit its report direct to the office of the Union.

Committee on Nominations,
A. G. McNish, Chairman,
R. R. Coats,
J. W. Greig

(g) Section of Hydrology--The Section has recently adopted a procedure to be followed for nominations and elections, but, because of delays which have occurred in adopting this procedure and in selecting the Committee on Nominations, the procedure specified cannot be followed completely for the forthcoming election as to dates, but it is being followed in all other respects.

Names of the candidates may be placed on the ballot in two ways: (1) By the Committee on Nominations, and (2) by petition signed by at least 25 members affiliated with the Section, and submitted to the Chairman of the Committee not later than January 31, 1947, together with a letter from each candidate thus proposed, consenting to his candidacy.

The Committee invites suggestions as to candidates from members of the Section. Such suggestions must be in the hands of a member of the Committee not later than January 15, 1947, for consideration and action by the Committee.

The Committee has full authority to decide on the number of candidates which may be proposed for any office, with the exception that the names of candidates proposed by a petition, signed by at least 25 members of the Section must be placed on the ballot.

The following have been selected as the Committee on Nominations to present a slate of candidates to be voted on for the offices of President, Vice-president, and Secretary of the Section, the elected candidates to serve for the term, 1947-1950: H. N. Eaton, Chairman; Richard A. Hertzler; Walter B. Langbein; S. W. Lohman; W. C. Lowdermilk; Morrough P. O'Brien; and Royce J. Tipton.

Herbert N. Eaton, Chairman,
Committee on Nominations,
Section of Hydrology

(h) Section of Tectonophysics--(1) Nominations are to be initiated by a small Committee on Nominations consisting of five members appointed by the President of the Section. (2) At least two persons shall be nominated for each of the offices of Section President, Vice-president, and Secretary, and, in addition, for the election of two members-at-large to the Executive Committee of the Section to hold office as long as the other officers. (3) The nominations are then to be announced to the membership and sufficient time provided before election to permit further nominations by petition. The petition shall be signed by at least 15 members affiliated with the Section, and the consent of each candidate shall be obtained before the petition is submitted to the office of

the Union, it being mandatory that nominations by petition be added to the official nominations. (4) Ballots containing official nominations and those submitted by petition are to be mailed to the membership and these ballots, postmarked before a specified date, are to be marked and forwarded by the membership to the office of the General Secretary. (5) The General Secretary, within ten days after the specified date, shall turn over all such ballots for tallying to a Committee of Tellers consisting of one member selected from each of the eight Sections and one member from the Executive Committee. (6) This Committee of Tellers is to make a report to the General Secretary within ten days showing the result of the ballot. (7) A plurality of votes cast shall elect.

The Committee on Nominations for the Section of Tectonophysics, for the officers to be elected in 1947 consists of N. L. Bowen, Chairman; Maurice Ewing; T. S. Lovering; W. W. Rubey; and L. B. Slichter.

Ernst Cloos, President,
Section of Tectonophysics

APPENDIX 7--REPORT OF COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

Merrill Bernard	**C. L. Garner**	**R. A. Hertzler**
G. B. Cressey		**W. D. Sutcliffe**

Your Committee notes with pleasure that the Section of Hydrology has arranged for regional meetings at Pasadena, California, and in the Pacific Northwest, and regrets that efforts to arrange for inter-divisional meetings on these occasions proved unsuccessful, because of the other engagements of interested members of other Sections in the areas concerned.

Your Committee regrets also that it proved impossible to arrange for a suggested inter-divisional regional meeting in the New England area this fall or winter, because of the heavy schedules of interested members in that section of the country, and particularly because of the meeting of the AAAS in Boston at Christmas, which is taking most of the available energy of our membership in New England.

Your Committee plans to arrange for a meeting of some or all Sections of the Union in New England at a time when academic engagements and weather are more favorable, if convenient, early next summer.

Your Committee recommends that the Annual General Meeting of the Union and of its Sections for 1947 be held in Washington, D. C., on Monday, Tuesday, and Wednesday, April 28, 29, and 30th. This will just precede the meeting of the American Physical Society, and, presumably, of the Division of Geology and Geography of the National Research Council. It is planned to use for meeting rooms the auditoria of the United States National Museum, and several of the other Federal auditoria.

APPENDIX 8--REPORT OF THE ACTING CHAIRMAN OF THE SPECIAL COMMITTEE ON NATIONAL WELFARE AND RELATED FUNCTIONS ON THE FUTURE OF THE COMMITTEE

Chester R. Longwell, Acting Chairman

Walter H. Bucher	**H. H. Hess**	**C. -G. Rossby**
Jno. A. Fleming	**W. T. Thom, Jr.**	**Harlan T. Stetson**
C. L. Garner	**E. S. Larsen**	**Waldo E. Smith**
H. D. Harradon	**James B. Macelwane**	**H. U. Sverdrup**

Word has come from a majority of the members of the Special Committee on National Welfare of the AGU, and therefore I advise you of the results of my conference with members of the Committee in order that you may formulate any plan regarding the Committee.

At least a majority of the committee members feel that the aims of the Special Committee have large merit and that it is well worth considering to have a group that will continue a study of the social obligations of science. On the other hand, most members of the Committee agree that the success of such a study depends on a chairman who believes thoroughly in the program and has time to devote to the necessary effort. If any special committee of this kind is to be continued in the AGU it will be necessary to find such a chairman, and it would not be desirable or fair to

ask such a man to take over a committee with a ready-made membership; he ought to have a free hand in choosing the men with whom he can work to best advantage. It seems, therefore, that the present committee should be dissolved, whatever action the Executive Committee may think best to take for the future. Some members have expressed the opinion, rather emphatically, that the formation of the new group in the International Union of Geodesy and Geophysics will make all the more necessary a national committee, not only in this country but in other countries, to cooperate in studying all aspects of the impact of science on society. No doubt your Executive Committee will weigh this matter, and if it decides that a committee of this sort is desirable it will try to find a chairman who is sympathetic with the program and will undertake to form a committee for this purpose. He might conceivably ask some members of the old committee to continue with him. On the other hand, it seems that he ought to have an entirely free hand in deciding on the make-up of the committee he is to administer.

APPENDIX 9--REPORT OF COMMITTEE ON RESOLUTIONS ON RESOLUTION PROCEDURE

Earl Ingerson, Chairman
N. H. Heck J. P. Marble

At its meeting of May 28, 1946, the Executive Committee indicated that the Committee on Resolutions has the authority to decide whether resolutions presented by Sections, other groups, or individuals, should be presented to the General Assembly of the Union. Events leading up to this discussion, however, emphasized the need for a more definite procedure. Accordingly, the following outline is recommended for adoption by the Executive Committee:

1. Each resolution must be accompanied by a letter, or written statement, giving the following information: (a) Name(s) of original submitter(s) of the resolution; (b) if presented to a Section, what action was taken, (1) if approved, by what vote, (2) other action; (c) whether action by the General Assembly is desired, or whether the resolution is merely to be read for the information of the Union.

2. If the Committee decides not to present a resolution to the Union it must so inform the submitter(s) of the resolution, before the General Assembly, if possible, so that it can be presented from the floor if such action is desired by the submitter(s).

3. The Committee must report all resolutions submitted to it, with appropriate recommendations, to the Executive Committee.

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SPECIAL ANNOUNCEMENTS

First announcement of Twenty-Eighth Annual Meeting, Washington, D. C., April 28 to 30, 1947--The Twenty-Eighth Annual Meeting of the American Geophysical Union will be held in Washington, D. C., April 28 to 30 (Monday to Wednesday), 1947. Sessions will be arranged to extend over three full days. Please note that the program dates for this meeting are about one month earlier than those of the Twenty-Seventh Annual Meeting.

This first announcement of the meeting is an invitation to communicate plans for papers. Titles and abstracts should be sent in as soon as possible, and not later than March 1, 1947, to the Secretaries of the Union and of the Sections, as follows:

The Union	Jno. A. Fleming Waldo E. Smith	5241 Broad Branch Road, N. W., Washington 15, D. C.
Geodesy	J. A. Duerksen	U. S. Coast and Geodetic Survey, Washington 25, D. C.
Seismology	L. M. Murphy	U. S. Coast and Geodetic Survey, Washington 25, D. C.
Meteorology	H. D. Harradon	5241 Broad Branch Road, N. W., Washington 15, D. C.
Terrestrial Magnetism and Electricity	D. G. Knapp	3827 W Street, S. E., Washington 20, D. C.
Oceanography	L. P. Disney	U. S. Coast and Geodetic Survey Washington 25, D. C.
Volcanology	Francis G Wells	U. S. Geological Survey, Washington 25, D. C.
Hydrology	K. H. Beij	National Bureau of Standards, Washington 25, D. C.
Tectonophysics	M. K. Hubbert	Shell Oil Company, Shell Bldg., Houston 2, Texas

The Chairman of the Committee on Meetings (J. P. Marble, Smithsonian Institution, Washington 25, D. C.) invites suggestions and comments bearing on the proposed meeting. Especially invited are offerings relating to papers and symposia bearing on more than one section.

Complete manuscripts of papers should be forwarded in triplicate by the end of March 1947. It is requested that authors preparing papers for presentation, and for publication in the Transactions refer to "Suggestions to Authors" [Trans. Amer. Geophys. Union, v. 26, pp. 179-182, August 1945], preparing reference material in accordance with the more recent procedure [Trans. Amer. Geophys. Union, v. 27, p. 306, April 1946]. Reprints of "Suggestions to Authors" may be secured from the office of AGU.

In transmitting papers and abstracts, advice should be given on time (most papers are allowed from ten to 20 minutes) and projection equipment required. If papers are written in collaboration, please indicate by whom they will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend the meeting. Papers for publication only are also welcome for consideration for the Transactions.

John Putnam Marble, Chairman,
Committee on Meetings

Notice regarding nominations and elections--Elections of President, Vice President, and General Secretary of the Union, and of all Section officers are to take place during the early months of 1947, and the new officers are to be installed as of July 1, 1947. The Statutes and By-Laws now provide that all of these officers shall be elected by mail ballot. The Committee on Nominations of the Union was charged with the responsibility of recommending procedures for the nomination and election of the Union officers. Their report, as approved, is published on page 910 of this issue. A time schedule, worked out jointly by the Committee on Nominations and the Office of AGU is also published (see p. 910).

SPECIAL ANNOUNCEMENTS

(Continued from preceding page)

Deviation must be made in this instance, because of the advanced date. Usually announcement of the "official nominees" will be made in the December issue of the Transactions, preceding an election year, but this year announcement will be made by special mail notification which should reach members before January 1, 1947. Note that provision is made for additional nominations by petition.

The procedures for nomination of officers of the Sections are found on pages 912 to 914 of this issue. They follow the Union procedure quite closely, except in the instance of the Section of Hydrology, in which case suggestions for nominations will be received until January 15. Nominations by petition will be received until February 1, the same as the Union and the other Sections. Names of "official nominees" will not be published in advance, but will appear for the first time, with nominees by petition, on the ballot.

A ballot covering all officers to be elected, both Union and Section, will be forwarded late in February 1947, to members in good standing, as provided in the "procedures." Be on the lookout for yours, mark it and return it promptly to the office of AGU.

Regional Meeting of Section of Hydrology in Pasadena, February 15, 1947--A Regional Meeting of the Section of Hydrology is to be held in Pasadena, California, Saturday, February 15, 1947. F. J. Veihmeyer, Davis, California, is Chairman of the South Pacific Regional Committee of the Section that is making plans for the meeting. Franklin Thomas of California Institute of Technology is in charge of local arrangements and the program. Inquiries and communications should be sent to Professor Veihmeyer or Professor Thomas.

Regional Meeting of the Section of Hydrology in Portland, Oregon in April 1947--A Regional Meeting of the Section of Hydrology is to be held in Portland, Oregon, Tuesday, April 22, and Wednesday, April 23, 1947. Preceding the Section meeting, a meeting of the Columbia River Forecast Committee will be held Monday morning, April 21; Monday afternoon and Tuesday morning, the Western Snow Conference will hold its meeting. The arrangements for the Section of Hydrology are in the hands of the North Pacific Regional Committee of the Section, J. C. Stevens, Chairman, and George G. West, Secretary. Inquiries and communications should be sent to Dr. Stevens, Spalding Building, Portland 4, Oregon, or to Mr. West, 628 Pittock Building, Portland 5, Oregon.

Changes of address and the new Directory--It is the plan to publish a new Directory of the membership of the American Geophysical Union as early as possible in 1947. Request is made for members to cooperate in forwarding changes of address promptly to the office of AGU. Directory Information Cards will be mailed to members with dues statements. Cooperation in the prompt return of these cards is likewise requested, whether or not change of address is involved.